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Volume 2

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THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES:

APPENDIX C - AGRICULTURE

Editors: Joel B. Smith and Dennis A. Tirpak

OFFICE OF POLICY, PLANNING AND EVALUATION
U.S. ENVIRONMENTAL PROTECTION AGENCY
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MAY 1989

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PREFACE

The ecological and economic implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years, members of Congress have held hearings on the greenhouse effect and have begun to examine its implications for public policy. This interest was accentuated during a series of hearings held in June 1986 by the Subcommittee on Pollution of the Senate Environment and Public Works Committee. Following the hearings, committee members sent a formal request to the EPA Administrator, asking the Agency to undertake two studies on climate change due to the greenhouse effect.

> One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

To meet this request, EPA produced the report entitled *The Potential Effects of Global Climate Change on the United States*. For that report, EPA commissioned fifty-five studies by academic and government scientists on the potential effects of global climate change. Each study was reviewed by at least two peer reviewers. The Effects Report summarizes the results of all of those studies. The complete results of each study are contained in Appendices A through J.

Appendix	Subject
A	Water Resources
B	Sea Level Rise
C	Agriculture
D	Forests
E	Aquatic Resources
F	Air Quality
G	Health
H	Infrastructure
I	Variability
J	Policy

GOAL

The goal of the Effects Report was to try to give a sense of the possible direction of changes from a global warming as well as a sense of the magnitude. Specifically, we examined the following issues:

- sensitivities of systems to changes in climate (since we cannot predict regional climate change, we can only identify sensitivities to changes in climate factors)
- the range of effects under different warming scenarios
- regional differences among effects
- interactions among effects on a regional level

- national effects
- uncertainties
- policy implications
- research needs

The four regions chosen for the studies were California, the Great Lakes, the Southeast, and the Great Plains. Many studies focused on impacts in a single region, while others examined potential impacts on a national scale.

SCENARIOS USED FOR THE EFFECTS REPORT STUDIES

The Effects Report studies used several scenarios to examine the sensitivities of various systems to changes in climate. The scenarios used are plausible sets of circumstances although none of them should be considered to be predictions of regional climate change. The most common scenario used was the doubled CO_2 scenario ($2XCO_2$), which examined the effects of climate under a doubling of atmospheric carbon dioxide concentrations. This doubling is estimated to raise average global temperatures by 1.5 to 4.5°C by the latter half of the 21st century. Transient scenarios, which estimate how climate may change over time in response to a steady increase in greenhouse gases, were also used. In addition, analog scenarios of past warm periods, such as the 1930s, were used.

The scenarios combined average monthly climate change estimates for regional grid boxes from General Circulation Models (GCMs) with 1951-80 climate observations from sites in the respective grid boxes. GCMs are dynamic models that simulate the physical processes of the atmosphere and oceans to estimate global climate under different conditions, such as increasing concentrations of greenhouse gases (e.g., $2XCO_2$).

The scenarios and GCMs used in the studies have certain limitations. The scenarios used for the studies assume that temporal and spatial variability do not change from current conditions. The first of two major limitations related to the GCMs is their low spatial resolution. GCMs use rather large grid boxes where climate is averaged for the whole grid box, while in fact climate may be quite variable within a grid box. The second limitation is the simplified way that GCMs treat physical factors such as clouds, oceans, albedo, and land surface hydrology. Because of these limitations, GCMs often disagree with each other on estimates of regional climate change (as well as the magnitude of global changes) and should not be considered to be predictions.

To obtain a range of scenarios, EPA asked the researchers to use output from the following GCMs:

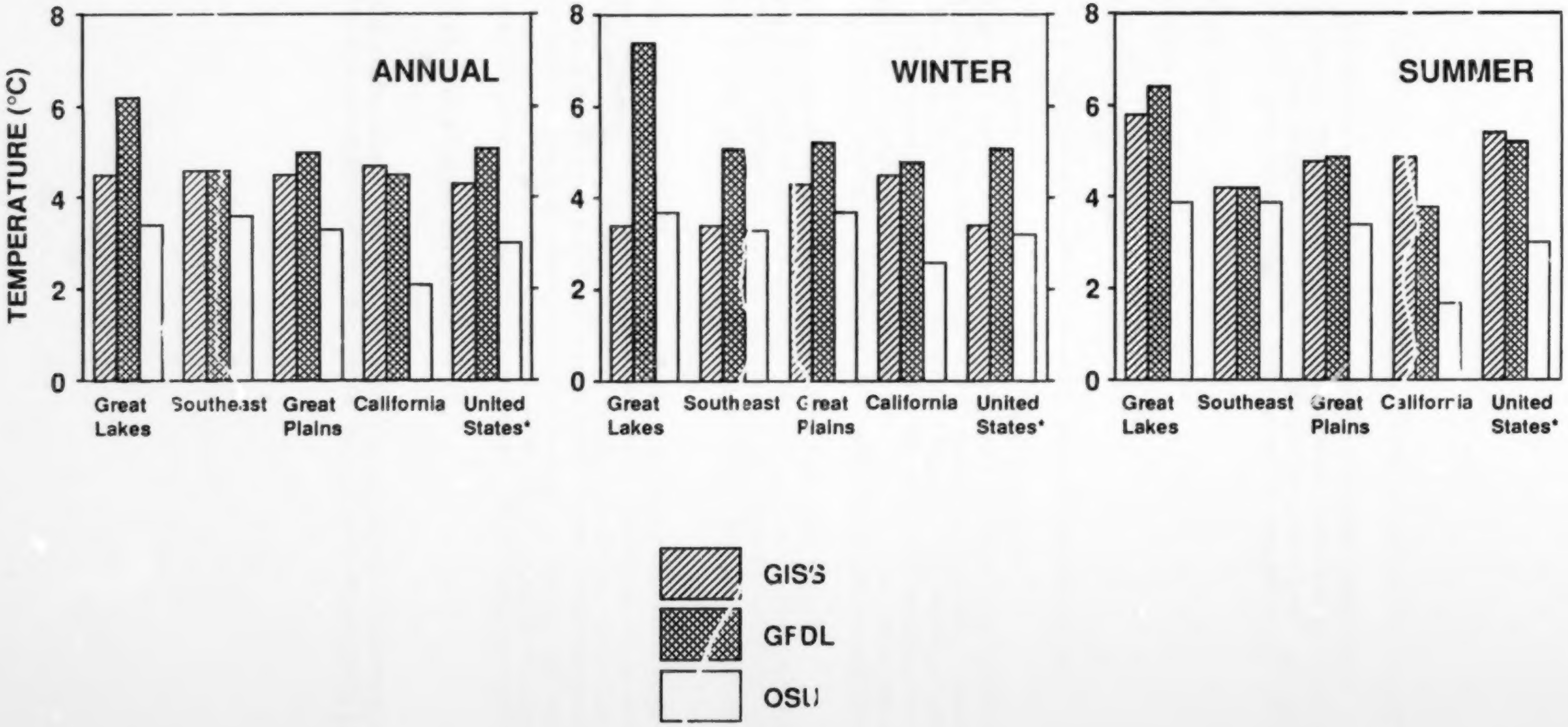
- Goddard Institute for Space Studies (GISS)
- Geophysical Fluid Dynamics Laboratory (GFDL)
- Oregon State University (OSU)

Figure 1 shows the temperature change from current climate to a climate with a doubling of CO_2 levels, as modeled by the three GCMs. The figure includes the GCM estimates for the four regions. Precipitation changes are shown in Figure 2. Note the disagreement in the GCM estimates concerning the direction of change of regional and seasonal precipitation and the agreement concerning increasing temperatures.

Two transient scenarios from the GISS model were also used, and the average decadal temperature changes are shown in Figure 3.

FIGURE 1. TEMPERATURE SCENARIOS

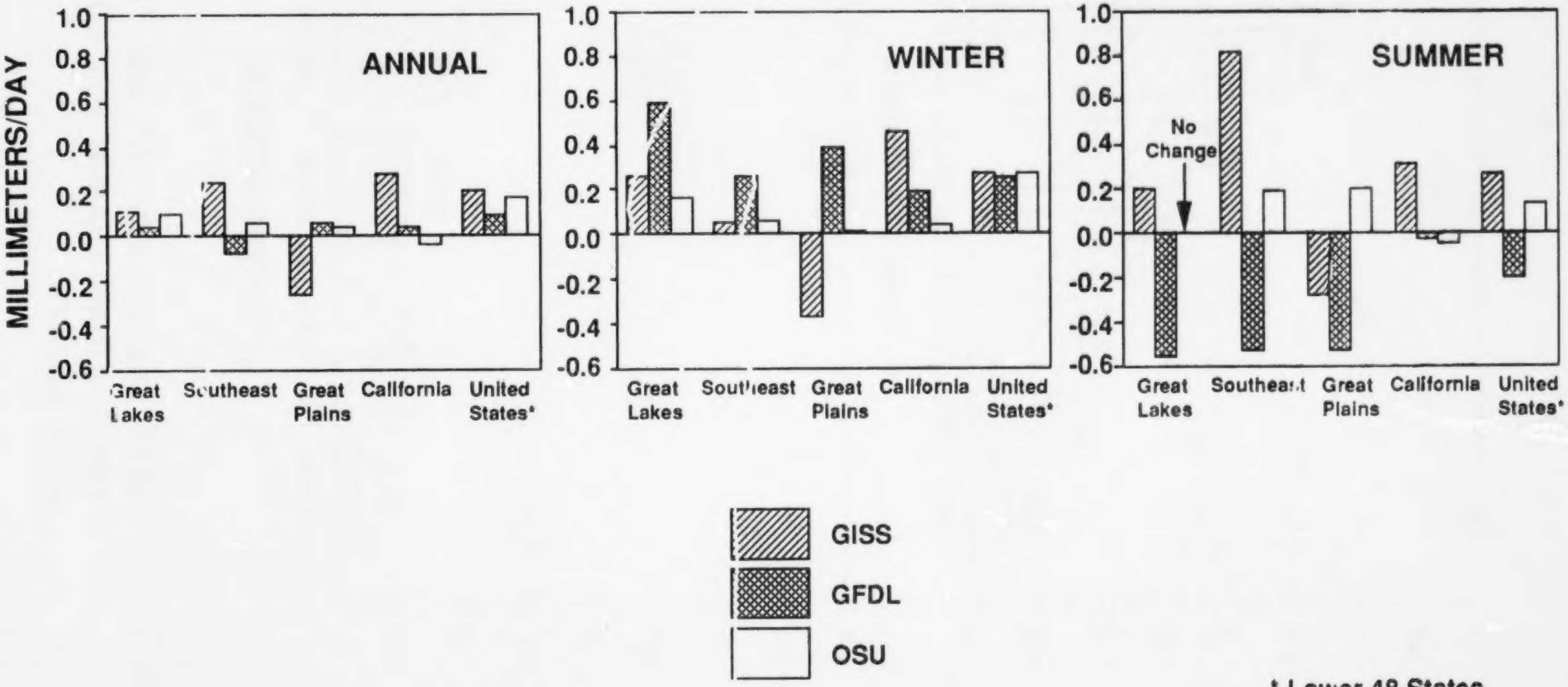
GCM Estimated Change in Temperature from $1xCO_2$ to $2xCO_2$



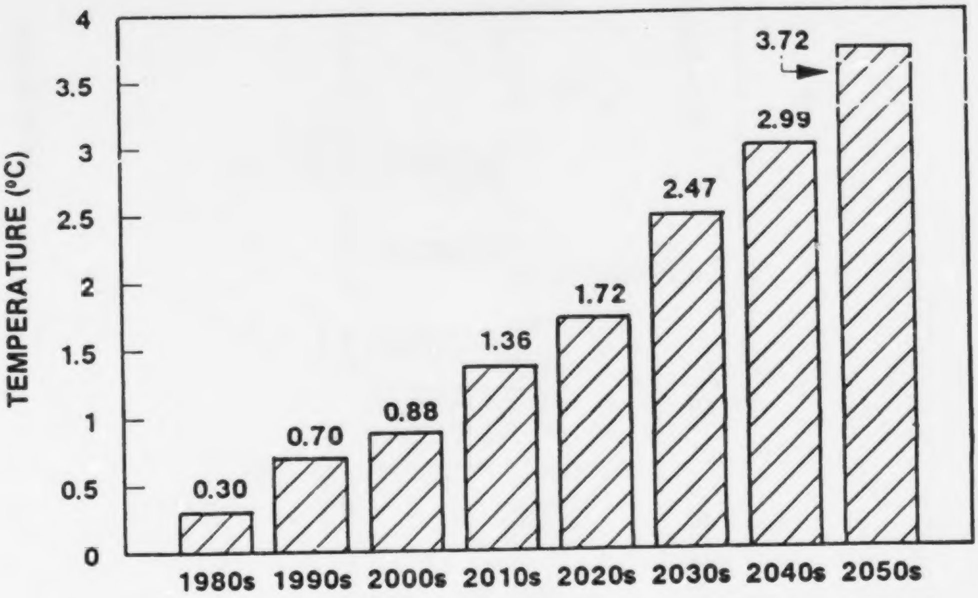
* Lower 48 States

FIGURE 2. PRECIPITATION SCENARIOS

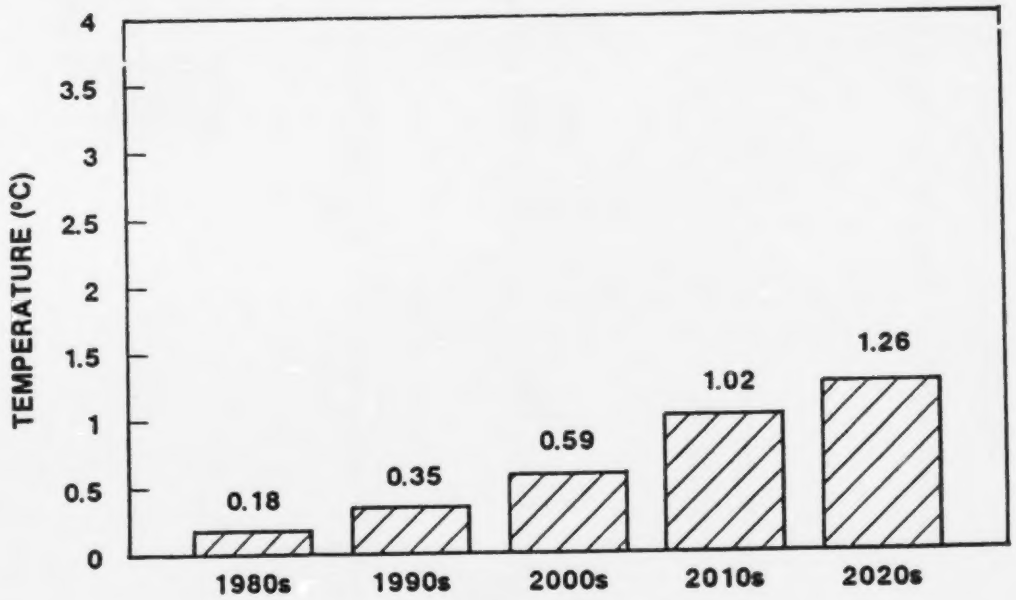
GCM Estimated Change in Precipitation from $1xCO_2$ to $2xCO_2$



* Lower 48 States



TRANSIENT SCENARIO A



TRANSIENT SCENARIO B

FIGURE 3. GISS TRANSIENTS "A" AND "B" AVERAGE TEMPERATURE CHANGE FOR LOWER 48 STATES GRID POINTS.

EPA specified that researchers were to use three doubled CO_2 scenarios, two transient scenarios, and an analog scenario in their studies. Many researchers, however, did not have sufficient time or resources to use all of the scenarios. EPA asked the researchers to run the scenarios in the following order, going as far through the list as time and resources allowed:

1. GISS doubled CO_2
2. GFDL doubled CO_2
3. GISS transient A
4. OSU doubled CO_2
5. Analog (1930 to 1939)
6. GISS transient B

ABOUT THESE APPENDICES

The studies contained in these appendices appear in the form that the researchers submitted them to EPA. These reports do not necessarily reflect the official position of the U.S. Environmental Protection Agency. Mention of trade names does not constitute an endorsement.

DIRECT (PHYSIOLOGICAL) EFFECTS OF INCREASING CO_2 ON CROP PLANTS AND THEIR INTERACTIONS WITH INDIRECT (CLIMATIC) EFFECTS

by

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Contract No. 68-01-7489

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FINDINGS[1]

- At moderate temperatures, most crops will probably show biomass increases and possibly yield increases as carbon dioxide concentrations rise.

- Leaf temperatures in all species are expected to rise even more than air temperatures, which may inhibit plant processes sensitive to high temperatures.

- Photosynthesis will increase in certain species and in some environments. If under certain conditions photosynthetic products accumulate, plants may regulate the level of photosynthetic CO_2 uptake rates through feedback inhibition of some enzymes or enhanced export of photosynthetic products out of the source leaves.

- Drought-stressed plants exposed to high partial pressures of CO_2 will be more able to cope with water deficits. Plants lacking adequate moisture will experience higher rates of photosynthesis and higher yields at enriched levels of carbon dioxide than at current CO_2 concentrations.

- Increasing air temperatures predicted by global climate change models will interact with all of the direct effects of enhanced concentrations of carbon dioxide, and will influence the direct effects over the life cycle of plants in ways that are not predictable with certainty at this time. The few exceptions to this uncertainty are the few areas where temperature and elevated concentrations of CO_2 have been studied simultaneously over the annual cycle or the whole life cycle of plants. Even these limited studies need to be verified with a range of crops and cultivars. Those studies indicate that the positive effects of carbon dioxide enrichment may be reduced or even eliminated at high temperatures.

- It is not clear whether plants' water use throughout their life cycles will increase, decrease, or remain the same as now. Stomata (leaf pores) in some environments close as levels of carbon dioxide rise. However, other environmental factors such as humidity, temperature, light, and soil moisture also affect stomata and other facets of water use. These effects may be more important than the amount of carbon dioxide in determining water use.

- Future research should include a range of higher temperatures similar to those predicted by the global climate change models, as well as higher partial pressures of carbon dioxide. Although more complex to conduct, experimental water-deficit scenarios also should be included in some future experiments.

- Experimental research should be integrated with efforts to model plant processes.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Contract No. 68-01-7489, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

Predicted global increases in atmospheric carbon dioxide are expected to influence plant metabolism, growth, and development in two ways. Elevated concentrations of CO_2 directly affect plant processes. Changes in the level of CO_2 are also expected to influence plants indirectly through predicted increases in temperature and changes in other climate variables such as precipitation and atmospheric humidity.

This paper reviews recent reports of experiments on the direct effects of increasing atmospheric carbon dioxide on crop plants. First, the general status of research on effects of increasing levels of carbon dioxide on plant behavior will be summarized, with remarks about different experimental techniques being used and current research needs. Then, general effects of CO_2 on particular plant processes across many species will be outlined. Finally, because each species responds to carbon dioxide in ways that are peculiar to its phenology, growth habit, and adaptation, the review will explore findings specific to four major U.S. crops. Literature since 1980 on soybean, wheat, cotton, and corn will be examined, with particular attention to interactions between the effects of elevated partial pressures of carbon dioxide, rising temperatures, and other environmental stresses. Plant growth models, which are useful research tools to explore the possible effects of rising levels of CO_2 but which differ substantially from an experimental approach, are not reviewed here.

STATUS OF RESEARCH

Research on the direct effects of CO_2 enrichment is most comprehensive for soybean, and photosynthesis is the plant process researched most extensively. In other species, research has concentrated on the influence of elevated amounts of carbon dioxide on yield, photosynthesis, stomatal responses, and water use, with little attention to other direct effects such as effects on leaf temperature, crop phenology, water potential, dark respiration, and photorespiration.

Investigations of the interactions between projected increases in global air temperature and direct effects of CO_2 on plant processes, including effects on economic yield, biomass accumulation, phenology, photosynthesis, stomatal responses, water use, water-use efficiency, the rise in leaf temperatures seen in all species, photorespiration, dark respiration, and nitrogen fixation are very limited. There have been a few studies relating the interactive effects of high levels of carbon dioxide and temperature on field and pot-grown soybean plants, three on wheat, two on forage grasses, and no temperature-controlled studies on other species.

Research to this point has usually provided windows of knowledge about certain crops at specific stages of their life cycles. Both direct and climate change effects of high amounts of CO_2 are probably quite different at different stages of development.

Experimental conditions and facilities. The literature is replete with studies lacking proper experimental design, particularly with regard to replication and randomization. Plants in the same field chamber, indoor growth chamber, or phytotron at the same time are not replicates of each other, but subsamples of the same replicate (Lee and Rawlings, 1982). This statistical safeguard was violated more often than it was observed. Also, very few investigators used proper randomization when assigning treatments in the open field or in chambers. Lee and Rawlings (1982) found great, nonrandom heterogeneity within and between chambers, which greatly affected soybean growth (accounted for 50 to 70% of the plant-to-plant variation) unless strict randomization was observed.

Any growth chamber or phytotron results should be examined with respect to light intensity, which is usually less than that of ambient conditions. Researchers have sometimes assumed that chamber experiments with longer, less intensive photoperiods are equivalent to shorter times in high-intensity outdoor environments as long as total photosynthetic energy (photosynthetic photon flux density or PPFD) is equal. Because of the interactions between light intensity and the photosynthetic response to CO_2, this assumption cannot be made for CO_2 studies.

Field chamber experiments in general lack this light intensity problem, and Havelka et al. (1984b) found no difference in yield or plant growth between field-grown or field chamber-grown wheat plants. But because there is no wind, natural air mixing is sometimes not replicated in closed and even some open-top chambers. Any experiments using pots probably can not be viewed as representative of field soil results because of the strong effects of root restriction on overall growth and even on the physiological processes involved. (Sionit et al., 1984; Rogers et al., 1986). Low-density canopies (individual plants) also do not represent typical field conditions where intraspecific competition takes place.

RECOMMENDATIONS FOR RESEARCH

Future research should be more comprehensive and multidisciplinary, integrated with modeling efforts and the experiments of other research teams. To account for interactions with temperature increases predicted by global climate change models, experiments should investigate the effects of carbon dioxide enrichment over a range of temperatures, including high temperatures. To minimize experimental artifacts, techniques should emphasize field research using randomly placed open-top chambers with crops planted directly in the field soil. Calculations indicate that such techniques are physically and economically feasible.

Major food crops that have had few experimental results published, including rice, corn, wheat, potatoes and sorghum, should be investigated for response to both elevated CO_2 concentrations and rising temperatures. Research on plant processes, which has concentrated on photosynthesis, should be broadened to include other metabolic events that affect yield.

Researchers should study the interactive effects of elevated carbon dioxide concentration and temperature over the whole life cycle of the plant, with plants grown under different water and nutritional regimes rather than with only "pampered" plants under optimal conditions. Then more realistic predictions of crop response to the combined climatic and physiological effects of rising CO_2 may be made.

With more data about these processes and better understanding of them, we can give a firmer foundation to crop growth models. These models in turn can integrate knowledge about CO_2 enrichment and global warming and refine their predictions of plant responses to the changing atmosphere.

CHAPTER 2

PLANT PROCESSES AFFECTED BY INCREASING CARBON DIOXIDE

YIELD

Yield can be expressed either as biomass accumulation (increases in total plant dry weight) or as economic yield (weight of seeds, fruits, cotton lint, soybean oil, wood, etc.). Yield is affected by dozens of different plant processes, including but not limited to photosynthesis, development of vegetative or reproductive organs (the latter being called yield components), water relations, and nutrient uptake, as well as the effect of environmental stresses on such processes and the length of the life cycle.

Economic yield and biomass accumulation. Most research groups have found increases in economic yield when plants are placed in enriched atmospheres of carbon dioxide at moderate temperatures. One reviewer who surveyed 70 prior reports calculated an average yield increase for C3 plants of 33% with a doubling of atmospheric CO_2 (Kimball, 1983). Plant dry weight has increased in most species that use the C3 photosynthetic pathway because of greater photosynthesis (see individual species sections on soybean, wheat, and cotton). Leaf area increased (Sionit et al., 1981b; Rogers et al., 1983a; Jones et al., 1984, 1985b; Kimball et al., 1984; Marc and Gifford, 1984; Morison and Gifford, 1984a; Chaudhuri et al., 1987; Wall and Baker, 1987) as did leaf thickness (Rogers et al., 1983b; Cure et al., 1986, 1987). Plants using the C4 pathway of photosynthesis also had higher yields, but apparently because of more favorable water relations rather than because of effects on carbon fixation (Carlson and Bazzaz, 1980; Rogers et al., 1983b; King and Greer, 1986). CO_2 enrichment also appeared to have little effect on plants using the crassulacean acid metabolism (CAM) photosynthetic pathway (Szarek et al., 1987), but only one notable crop species, pineapple, uses this pathway.

Yield components. C3 species exposed to high levels of CO_2 responded by producing more vegetative or reproductive organs, as well as by enhancing organ size. Increasing CO_2 concentration often had a positive effect on initiation rate of vegetative organs such as leaves in many species (Chaudhuri et al., 1986; Schonfeld, 1987), as well as on the rate of leaf expansion. The resultant increase in leaf area per plant also further enhanced overall photosynthate production. Plants also initiated more reproductive structures. The numbers of flowers per cotton plant (Kimball et al., 1986, 1985, 1984, 1983), of tillers in wheat, which determines the number of potential heads (Marc and Gifford, 1984; Schonfeld, 1987), and of soybean seeds per plant (Rogers et al., 1984a; Cure et al., 1986; Sionit et al., 1987) and pods per plant (Ackerson et al., 1984) increased with exposure to high carbon dioxide concentrations.

Phenology. Crop yield depends in part on the rate of filling pods, seeds, grains, or bolls with products of photosynthesis and other synthetic pathways, times the duration of the filling periods. Higher temperatures cause plant phenology (the progress through its life cycle) to speed up, leaving less time in these filling stages for carbon and nitrogen accumulation. With the rate of net photosynthesis increasing, but the duration of grainfill shortened, yields may not differ from present levels. Determinant plants, with a fixed length of life cycle, would not benefit from accelerated phenology; but indeterminant plants, which can continue reproducing indefinitely if provided with enough nutrients, would be able to produce more if their life cycles were speeded up. Ackerson et al. (1984) found indeterminate soybeans were more responsive to CO_2 enrichment than were determinate varieties.

King and Greer (1986) reported accelerated phenology in corn was correlated with carbon dioxide enrichment at moderate temperatures. Floral initiation was advanced in wheat and sunflower, but the rate of floral differentiation was retarded slightly in wheat and significantly in sunflower exposed to high concentrations of CO_2 (Marc and Gifford, 1984).

PHOTOSYNTHESIS

Biochemically, yield increases depend in part on increases in photosynthesis, the process by which green plants use light energy to form sugar molecules from carbon dioxide and water. Photosynthesis is usually expressed as the net CO_2 assimilation rate, or the rate at which the gas is extracted from the air and added to the plant mass, minus any CO_2 lost through respiration or photorespiration.

If the concentration of carbon dioxide in the air rises, so does the diffusion gradient between the outside of the leaf, which is rich in CO_2, and the inside of the leaf, where the molecules are continually being used up by the reaction. As a result, more carbon dioxide will diffuse into the leaf.

We might think of photosynthesis as an assembly line. Since carbon dioxide is one substrate or raw material for this reaction, the more CO_2 provided to the plant machinery, the more products (sugars and other carbohydrates such as starch) could be made, and the more the plant could grow or yield. Accordingly, some research supports the contention that photosynthesis is expected to increase at moderate to high temperatures for most C3 plants (see Kimball review, 1983). Because global warming is expected as atmospheric CO_2 increases, this enhancement of photosynthesis may pertain in many environments.

FEEDBACK INHIBITION

However, a number of groups observed that plants acclimated to higher substrate levels and eventually drifted down to a photosynthetic rate similar to that in plants grown in existing concentrations of carbon dioxide at low temperatures (Azcon-Bieto, 1983; Coyne and Bradford, 1984; Idso et al., 1987b) and moderate temperatures (Clough et al., 1981; Azcon-Bieto, 1983; Coyne and Bradford, 1984; Peet, 1984; Sionit et al., 1984; DeLucia et al, 1985; Sasek et al, 1985; Breen et al., 1986; Rogers et al., 1986). Several mechanisms could have been involved in the acclimation process.

Carbohydrate accumulation. The carbohydrate end products of the reaction may have built up to a higher level than could be processed by the plants' metabolizing enzymes, and beyond the ability of the plants to transport them away from the site of photosynthesis. This would clog the machinery and slow down the process.

Sucrose is the major end product of photosynthesis in most leaves and the form of carbohydrate most often exported to the rest of the plant (Stitt et al. 1984a). Sucrose can be converted to starch, an insoluble end product used primarily for growth of shoots (stems and source leaves) in the dark. So carbon partitioning between the two compounds affects carbon allocation and growth of the various plant parts (Huber, 1983).

The concentration of sucrose in the leaf helps control the rate of translocation from source leaves (Huber, 1983; Huber et al., 1984; Stitt et al., 1984b). Export rises with leaf sucrose level until the latter reaches 12 mg per dm^2, when export levels off (Huber et al., 1984). High leaf sucrose levels, such as were found in plants grown in high concentrations of CO_2 (Ackerson et al., 1984; Gent, 1984; Huber et al., 1984), inhibited the enzyme that controls its synthesis, sucrose phosphate synthase.

High concentrations of leaf sucrose also promoted starch synthesis. Thus more photosynthate was retained in the leaf and converted to starch, which cannot be exported from the chloroplast (Huber, 1983; Huber et al., 1984; Stitt et al., 1984b). Huber et al. (1984) found that essentially all the extra carbon fixed by soybean plants under carbon dioxide enrichment was partitioned into starch; sucrose export did not increase over plants in ambient CO_2.

The accumulation of carbohydrates has been associated with feedback inhibition of photosynthesis at various species-dependent temperatures (Clough et al., 1981; Azcon-Bieto, 1983; Peet, 1984; DeLucia et al., 1985; Sasek et al., 1985; Breen et al., 1986; Sage and Sharkey, 1987). This end-product inhibition could even cause carbon fixation to decrease relative to current levels in some species and climates as global levels of carbon dioxide rise.

Source-sink relationships. The strength of sinks (growing organs that receive the products of photosynthesis) has been shown to affect photosynthesis and growth of plants in elevated atmospheres of carbon dioxide (Clough et al., 1981; Peet, 1984; Sasek et al., 1985; Cure et al., 1987). In each case, plants with greater sink strength had greater photosynthesis. Apparently plants need plenty of places to send their newly synthesized carbohydrates before they will respond photosynthetically to rising levels of CO_2, which is probably linked to carbohydrate accumulation discussed above.

Ackerson et al. (1984) placed soybean plants in enriched atmospheres of carbon dioxide at different stages of their life cycle. Plants showed seed yield increases only when given extra CO_2 at times when there was a heavy sink load, especially at podfill. These results suggest that breeders may want to select plants with greater sink capacity to cope with and to take better advantage of increasing carbon dioxide.

Azcon-Bieto (1983) found that treatments which reduced the rate of translocation of carbohydrates from mature wheat source leaves to sinks (such as lowering the ambient temperature or chilling the base of the leaf) produced marked reductions in carbon uptake at CO_2 partial pressures of 340, 700, or 825 μbars.

The source-sink ratio affected enzymes that control the concentrations of sucrose and starch in the source leaves (Rufty and Huber, 1983), which in turn could control photosynthesis and translocation (see above). Carbon dioxide enrichment also reduced the sucrose uptake capacity of field-grown sugar beet taproots, which could limit carbon flux from the source to this sink (Wyse and Saftner, 1982), again causing carbohydrate accumulation in the source leaves. However, translocation from source leaves in two ecotypes of barnyard grass (a C4 plant) was enhanced by high levels of CO_2. CO_2 enrichment also helped the plants overcome inhibition of export at cool temperatures. High rates of export, which reduced leaf sucrose concentration, were associated with higher net photosynthesis (Potvin et al., 1984).

Experimental conditions. The buildup of carbohydrates in storage organs (such as roots, tubers, or bulbs) differs in field-grown and pot-grown plants, and affects feedback inhibition of photosynthesis. There are also other differences, such as plant reactions to soil strength or nutrients and presence of intraspecific competition, between the two conditions. In two careful experiments, field soil-grown soybeans did not show the same increase in photosynthesis under very high levels of CO_2 as seen in plants grown outdoors in pots (Sionit et al., 1984; Rogers et al., 1986). Therefore care must be taken to express uncertainty when extrapolating from experiments done in pots to projected results in the field.

Photosynthesis is also known to be affected by transpiration (the loss of water by the plant), which in turn depends on several environmental factors, such as humidity, wind speed, temperature, soil water, and solar radiation. Although evapotranspiration rates in closed chambers have been measured as comparable to those in the open field (Jones et al., 1984; 1985a,b,c,d), experiments done in closed chambers usually do not duplicate outside wind speed and probably do not have internally uniform temperature and humidity (Lee and Rawlings, 1982), and therefore must also be interpreted with caution.

Photosynthetic regulation. Alternatively, just because they have more raw material to work with, the very sensitive machinery of photosynthesis (enzymes) may not be able to work faster, especially at temperatures that are too low or too high for their optimum functioning (Hofstra and Hesketh, 1975). There could be another type of adjustment (not depending on carbohydrate accumulation) of enzyme activity to keep the plant operating homeostatically. Porter and Grodzinski (1984) found a drop in activity of two enzymes of carbon fixation, carbonic anhydrase and ribulose bisphosphate carboxylase (rubisco), in 21-day-old bean plants after 7 days' exposure to 1200 μL/L CO_2, when they had demonstrably larger leaf area and dry weight than plants grown in 330 μL/L CO_2. Vu et al. (1983), working with field-grown soybeans, also found extractable carboxylation activity of rubisco, the chief photosynthetic enzyme, reduced up to 22% early in the season by carbon dioxide enrichment. The substrate for the enzyme (other than CO_2), ribulose bisphosphate, built up in these leaves, indicating that the plant machinery could not handle all the extra carbon dioxide (Vu et al., 1983).

Among some natural species and cultivated varieties, photosynthesis is maintained at similar rates over a wide range of environmental conditions (Holtum et al., 1983; Coyne and Bradford, 1984; Korner et al., 1988;

Sasek et al., 1985; Sionit et al., 1984; Rogers et al., 1986). Korner et al. (1988) found that plants at high altitudes, where the carbon dioxide concentration is low, maintained a rate of carbon assimilation relative to their internal CO_2 concentration that was similar to that in low-altitude plants. In other words, the plants adjusted for the lower CO_2 concentration by becoming more efficient at trapping carbon dioxide.

Similarly, Holtum et al. (1983) found that stomatal aperture in the CAM plant Kalanchoe daigremontiana adjusted to changing CO_2 partial pressures to maintain an approximately constant ratio of diffusion resistance to carboxylation (nonstomatal) resistance in a variety of environmental conditions. Over the entire dark period, net carbon uptake was similar for plants in 100, 330, or 1000 μbar CO_2. Malate accumulated to the same level in every treatment, and then CO_2 assimilation shut off. So carbon uptake was not controlled by external CO_2 level but by "innate plant control."

Coyne and Bradford (1984) observed nonstomatal resistance to carbon assimilation in Caucasian Bluestem, a C4 perennial grass, increased greatly as CO_2 concentration rose, especially at low temperatures (15°C). Machler et al. (1986) found active inorganic carbon uptake in Trifolium repens L., a C3 clover, was more efficient at lower partial pressures of CO_2. Plants often seem to have their own optimal photosynthetic rate, and they will adjust amounts or activities of enzymes to maintain this homeostasis.

Some investigators expect a damping of the effects of increased CO_2 concentrations on photosynthesis, with long-term acclimation and over a large land area, compared to the dramatic photosynthetic increases seen in short-term chamber experiments (Cough et al., 1981; Azcon-Bieto, 1983; De Lucia et al., 1985; Sionit et al., 1984; Rogers et al., 1986). Others have found no decline in photosynthetic rates with prolonged exposure to high levels of CO_2 (e.g., soybean, Jones et al., 1985a,b,c; cotton, Radin et al., 1987). Until comprehensive experiments are done accounting for the numerous factors influencing plant growth, it is uncertain whether photosynthesis will increase greatly, slightly, or not at all among the wide range of crop species.

OTHER CARBON-EXCHANGE REACTIONS

Dark respiration. As discussed above, the apparent rate of net photosynthesis is affected by reactions where the plant loses carbon dioxide. Dark respiration (the "burning" or oxidation of sugars as fuel to yield energy) has been reported both to decrease (Reuveni and Gale, 1985) and to increase (Jones et al., 1985c) as CO_2 concentration rises, thus producing an uncertain effect on net carbon fixation.

Gifford et al. (1985) found the response differed with species. Respiration in wheat roots or whole plants grown in high partial pressures of carbon dioxide declined up to 50%, and the contribution of the wasteful alternate pathway was reduced. However, mung bean root respiration was unaffected by, and sunflower root cytochrome respiration was increased by, CO_2 enrichment. Any gain in carbon balance created by a reduction of respiration could be offset by a speed-up in dark respiration induced by higher temperatures.

Photorespiration. Rising CO_2 and warmer temperatures also have opposite effects on photorespiration (the oxygen-dependent inhibition of photosynthesis found only in C3 plants). Increasing the concentration of CO_2 itself caused photorespiration to fall, especially as a percentage of net carbon fixation (Peterson, 1983; Vines et al., 1983; Valle et al., 1985a; Kobza and Edwards, 1987), as the rubisco enzyme shifted from oxygenase to carboxylase (Vines et al., 1983). But this effect leveled off at CO_2 concentrations above 600 μL/L (Peterson, 1983).

On the other hand, higher temperatures, especially those above 40°C (Wynn, 1981; Monson et al., 1982), enhanced photorespiration (Wynn, 1981; Monson et al., 1982; Azcon-Bieto, 1983; Perry et al., 1983; Espie and Colman, 1987; Kobza and Edwards, 1987). In cotton, photorespiration used up half the CO_2 fixed in net photosynthesis at 40°C (Perry et al., 1983).

Extractable activity of rubisco decreased as temperatures increased from 15 to 45°C in wheat (Kobza and Edwards, 1987). The compensation point for CO_2 (the concentration at which the rate of photosynthetic CO_2

uptake equals the release of CO_2 from photorespiration and dark respiration) rose with temperature, indicating weaker binding between CO_2 and rubisco at hotter temperatures (Monson et al., 1982; Espie and Colman, 1987). Kobza and Edwards considered photosynthesis at supraoptimal temeratures was mainly limited by the activation state of rubisco and by the rise in the oxygen/carbon dioxide solubility ratio.

Photosynthesis decreased greatly from 25 to 45°C, even under the nonphotorespiring conditions of CO_2 at 800 μL/L and 2% O_2, for wheat (Azcon-Bieto, 1983; Kobza and Edwards, 1987) and for Agropyron smithii, another C3 grass (Monson et al., 1982). So while it is not clear which effect will prevail, work done with both high CO_2 concentrations and high temperatures (Monson et al., 1982; Azcon-Bieto, 1983; Kobza and Edwards, 1987) suggests photorespiration will increase with climate change, causing the rate of carbon fixation to be somewhat less than expected.

STOMATAL RESPONSES

Effects of enhanced carbon dioxide concentrations on behavior of stomata (the leaf pores) can be reported in terms of stomatal conductance, a measure of the ease with which water vapor passes out of the leaf, or in terms of its reciprocal, stomatal resistance, a measure of the difficulty with which water vapor exits the leaf. Both depend upon degree of stomatal aperture and are generally thought to be affected by evaporative demand, which increases with higher vapor pressure deficit (VPD, the difference between saturation vapor pressure at that temperature and actual vapor pressure). Recently Idso (1987) and Idso and Allen (1988) have cast doubt on the latter theory, contending that stomata are insensitive to VPD and respond only to internal indicators of water stress. Idso and Allen viewed results which contrasted with this theory as artifacts of porometry.

For C3 plants, it is not clear whether or not there are significant increases in stomatal closure due to enriched atmospheres of CO_2. The response seems to depend upon the species, the dryness of the air, and whether or not the plant is undergoing water deficit stress (see sections on soybeans, wheat, and cotton). In general, C4 plants seem to respond to higher levels of carbon dioxide by closing their stomata (Carlson and Bazzaz, 1980; Morison and Gifford, 1983; 1984; Rogers et al., 1983a,b; King and Greer, 1986).

Morison and Gifford (1983) seem to resolve some confusion (but not the claims of Idso and Allen) by demostrating that two C3 species were as sensitive to increasing carbon dioxide concentrations as two C4 species. Sensitivity of stomatal conductance to changes in CO_2 concentration were linearly proportional to the magnitude of stomatal conductance, as determined by VPD, with the same slope for all four species. In other words, at low concentrations of CO_2, low VPD and high conductances, sensitivity to changes in the level of CO_2 was greatest. In a later review, Morison (1985) analyzed others' data and determined that with a few exceptions related to the internal status of the plant (such as hormone concentration), their observations also fit this slope.

Surveying the response of 16 agricultural species to carbon dioxide enrichment, Morison and Gifford (1984) found stomatal conductance decreased by an average of 36%. Several researchers have found the internal carbon dioxide concentration of the plant, which is affected both by ambient CO_2 levels and by CO_2 uptake in photosynthesis, was more important in determining stomatal behavior than was ambient CO_2 concentration (Holtum et al., 1983; Morison and Gifford, 1983; Mott, 1988). Increasing air and leaf temperatures caused stomatal closure in a number of species (Monson et al., 1982; Idso et al., 1987b), which affected transpiration and water use.

TRANSPIRATION AND WATER USE

Transpiration measures how much water exits the plant. Both transpiration and water use by C3 plants in enriched atmospheres of CO_2 have been seen to increase, to decrease, or to remain the same when compared to control plants. Stomatal closure, seen in some C3 species and in almost all C4 species (see Gifford and Morison, 1985, for an exception), can result in water savings. For species using the C4 photosynthetic pathway, decreases in transpiration due to closure of stomata will probably be the most significant positive effect of elevated amounts of CO_2 (Carlson and Bazzaz, 1980; Morison and Gifford, 1983; Rogers et al., 1983a,b; King and Greer, 1986). However, the predicted global temperature increase may cancel out this effect by increasing vapor pressure deficit and therefore demand for transpiration, unless the Idso and Allen (1988) hypothesis is correct.

But even for plants that show increased stomatal resistance upon exposure to high concentrations of CO_2, transpiration per plant or area of ground may not decrease or may even increase. Plants grown in high levels of carbon dioxide always had higher leaf temperatures, and almost always a greater leaf area than plants grown in existing atmospheric concentrations of carbon dioxide (Morison and Gifford, 1984). Both these factors increased transpiration, elevating water use. The outcome in the case of global rise in amounts of carbon dioxide is unclear and will depend on species, relative humidity or vapor pressure deficit, leaf temperature, and soil moisture.

LEAF TEMPERATURE

Transpiration cools plants by using heat energy to change its water from a liquid state in the leaf to water vapor. Partial closure of the stomata restricts the transpiration rate and causes leaf temperature to rise. Leaf temperatures have risen 1 to 3°C or more with exposure to elevated concentrations of carbon dioxide in all species surveyed thus far (Perry et al., 1983; Morison and Gifford, 1984; Rogers et al., 1984b; Kimball et al., 1985; Chaudhuri et al., 1986, 1987; Idso et al., 1987a,b). These hotter leaf temperatures are the one phenomenon universally observed when high levels of CO_2 are applied.

These results logically follow the stomatal closure seen in some cases with high concentrations of CO_2. But more surprisingly, leaf temperatures have been observed to rise when there was no stomatal closure, by researchers working with soybeans (Rogers et al., 1984b), wheat (Chaudhuri et al., 1986, 1987), and cotton (Kimball et al., 1985).

When combined with the predicted warmer air temperatures, these hotter leaf temperatures could lead to biochemically based inhibition of growth and yield as sensitive enzymes react to potentially denaturing conditions (Hofstra and Hesketh, 1975; Monson et al., 1982; Azcon-Bieto, 1983; Kobza and Edwards, 1987). As higher temperatures and vapor pressure deficit cause greater evaporation from the soil, more severe drought stress could combine with these high leaf temperatures to create damage too great to be offset by any CO_2 enrichment-induced yield increase.

TEMPERATURE INTERACTIONS

Because rising levels of CO_2 are predicted to cause a global climate change, it is very important that we investigate the effects of increased carbon dioxide concentration as it interacts with the concomitant warming. However, experimental research has not dealt frequently with simultaneous indirect and direct effects on plants, so it is difficult to assess the relative contributions of the two variables, CO_2 enrichment and higher temperatures, to predicted responses of plants.

High temperatures alone inhibited photosynthesis and other enzymatic reactions in CAM plants (Martin and Siedow, 1981) as well as in C3 plants, where photorespiration increased with temperature, especially above 40°C (Wynn, 1981; Monson et al., 1982; Perry et al., 1983; Espie and Colman, 1987; Kobza and Edwards, 1987). As temperatures rose, binding between CO_2 and rubisco weakened (Monson et al., 1982; Espie and Colman, 1987).

More relevant studies examined the effects of several CO_2 concentrations at various temperatures. Wheat photosynthesis was optimal at 25°C and decreased greatly at 35°C and 45°C, even under the nonphotorespiring conditions of CO_2 at 800 μL/L and 2% O_2 (Azcon-Bieto, 1983; Kobza and Edwards, 1987). Similar inhibitory results of high temperature on photosynthesis despite elevated carbon dioxide concentrations were found in Agropyron smithii, another C3 grass (Monson et al., 1982).

Temperature sensitivity may reside in photosynthetic enzymes, which also change with exposure to high concentrations of CO_2. At temperatures above 40°C, irreversible enzyme damage and uncoupling of photophosphorylation occurs in both species mentioned above (Monson et al., 1982; Azcon-Bieto, 1983; Kobza and Edwards, 1987). Extractable activity of rubisco and fructose 1,6-bisphosphatase decreased as temperatures increased from 15 to 45°C in wheat (Kobza and Edwards, 1987). Kobza and Edwards considered photosynthesis at supraoptimal temperatures to be mainly limited by the activation state of rubisco and by the rise in the oxygen/carbon dioxide solubility ratio.

In several cases, increasing air temperatures were related to intensification of CO_2 enrichment effects, including rising leaf temperatures (Chaudhuri et al., 1987) and enhanced yields (Idso et al., 1987a,b; Kimball et al., 1986). However, in at least two crops, higher air temperatures combined with high CO_2 concentrations did not favorably affect plant development and yield over the whole season in spring wheat (Wall and Baker, 1987) or for several days in soybean (Jones et al., 1985a).

In Trifolium repens L., a C3 clover, CO_2 enrichment and increasing temperatures had opposite effects on CO_2 entry into the plant. Active inorganic carbon uptake was more efficient at 30°C than at 10°C, but was inhibited by increasing concentrations of CO_2 (Machler et al., 1986). Machler et al. interpreted the temperature phenomenon to the greater permeability of membranes at higher temperatures. Jurik et al. (1984) found the temperature optimum for carbon exchange in bigtooth aspen shifted from 25°C in 320 μL/L CO_2 to 37°C in 1900 μL/L CO_2. However, the initial slope of the CO_2 response curve of CER at 20°C leaf temperature did not differ from that at 30°C (Jurik et al., 1984).

Overall, when plants were given both high CO_2 concentrations and high temperatures, it seems the deleterious effects of high temperature prevailed over the beneficial effects of carbon dioxide enrichment.

DROUGHT STRESS

Drought can consist of episodes of water deficit stress which vary in severity, duration, and stage of the plants' life cycles at which they occur. These latter factors affect the plants' responses to water deficits. Because of these complexities, it is not usually possible to directly compare research studies. However, a general pattern of plant behavior that occurs when plants are deprived of water and given enriched atmospheres of CO_2 does emerge.

Depriving plants of adequate water had a very significant influence on their reaction to increased amounts of carbon dioxide. In general, drought-stressed plants seemed to benefit more than did well-watered plants from additional amounts of CO_2. Drought-stressed plants exposed to high concentrations of carbon dioxide maintained yields higher than those of nonstressed plants at current levels of CO_2 (Gifford, 1979; Jones 1985d; Kimball et al., 1986). Water deficits also affected stomatal reaction to CO_2 enrichment of air (Rogers et al., 1984b).

But for some species, there is evidence that depending on the severity and duration of the water deficit, the drought-induced inhibition of photosynthesis may not be overcome by photosynthetic increases due to enhanced CO_2 (Gifford and Morison, 1985; King and Greer, 1986; Chaudhuri et al., 1987, Schonfeld 1987; Vu et al., 1987).

Rogers et al. (1986), noting that plants confronted with nutrient deficiencies or high leaf temperatures may not be able to benefit from extra carbon dioxide, tentatively suggested that drought stress is the only stress that does not cancel enriched-CO_2 enhancement of growth and yield.

WATER-USE EFFICIENCY

Water-use efficiency (WUE) is a measure of the expenditure of water necessary to produce a certain amount of yield, which can be expressed as grain yield, gross biomass accumulation, or carbon dioxide molecules assimilated. In all cases studied, water-use efficiency has improved as CO_2 concentration has increased. For C3 species, WUE rose because high photosynthesis increased yield. For C4 species, WUE improved because stomatal closure caused less water to be expended (Morison and Gifford, 1984).

CHAPTER 3

SOYBEAN

Soybean (Glycine max L.), the most important oilseed crop in the world, is a C3 legume that originated in China. Acreage in the U.S., which produces half the world's supply, has increased enormously since 1945 (Wilcox and Leffel, 1987). Soybean is grown for a number of products, including oil and its byproducts such as plastics, fermented bean for tofu and soy sauce, vegetable protein for processed foods, and animal feeds (Coulman, 1987; Roecklein and Leung, 1987; Wilcox and Leffel, 1987).

The effects of elevated atmospheres of carbon dioxide have been studied more extensively on soybean than on any other crop. Despite this fact or perhaps because of it, the findings remain contradictory and confusing. Some of the discrepancies in results may be due to differences in experimental conditions that are known to influence responses to CO_2.

YIELD

Biomass accumulation. In all cases studied, raising the concentration of carbon dioxide causes increases in the total soybean plant mass at harvest (Carlson and Bazzaz, 1980; Clough et al., 1981; Finn and Brun, 1982; Rogers et al., 1983a,b, 1984a, 1986; Sionit, 1983; Havelka et al., 1984a; Jones et al., 1985d; Cure et al., 1986, 1987; Allen et al., 1987, 1988). These increases in whole-plant dry weight relative to control were seen throughout the life of the plant (Allen et al., 1987; Cure et al., 1987).

The first increments of added carbon dioxide (i.e., enriching the concentration of CO_2 from 332 to 428 $\mu L/L$ rather than from 772 to 910 $\mu L/L$) make the most difference in biomass, but the maximum increase in total vegetative dry weight was 66% at 910 $\mu L/L$ (Rogers et al., 1984a).

One group reported that the dry weight increase due to enriched atmospheres of carbon dioxide was proportionate among vegetative plant parts (Rogers et al., 1984a), but many investigators have reported increased leaf weight (Finn and Brun, 1982), leaf area (Rogers et al., 1983a; Ackerson et al., 1984; Jones et al., 1984, 1985b) and leaf thickness (Rogers et al., 1983b; Cure et al., 1986, 1987), including an extra layer of photosynthesizing palisade mesophyll cells (Rogers et al., 1983b; Campbell et al., 1987).

Yield components and seed yield. Plants grown in atmospheres elevated in carbon dioxide had higher seed yields (Rogers et al., 1983b, 1984a; Ackerson et al., 1984; Havelka et al., 1984a; Jones et al., 1985d; Cure et al., 1986; Allen et al., 1987; Sionit et al., 1987) by increasing branching (Ackerson et al., 1984), the number of seeds per plant (Havelka et al., 1984a; Rogers et al., 1984a; Cure et al., 1986; Sionit et al., 1987) or pods per plant (Ackerson et al., 1984), and sometimes raised the weight per seed as well (Cure et al., 1986).

However, elevated biomass did not always translate into increases in soybean seed yield (Rogers et al., 1986), because the harvest index (percent of mature plant weight that is seed yield) tended to decline with carbon dioxide enrichment (Rogers et al., 1984a, 1986; Cure et al., 1986), although Havelka et al. (1984) found no change in harvest index. Allen et al., (1988) also noted a slight decrease in harvest index, but contended that the main effect of CO_2 enrichment seemed to be increasing photoassimilation by soybean canopies while maintaining consistent allometric relationships (i.e., similar relative weight gains by various plant parts). They found few differences in partitioning between CO_2 treatments from 330 to 800 $\mu mol\ CO_2/mol$ air. High concentrations of carbon dioxide also had deleterious effects on the percent protein of seeds (Rogers et al., 1984a).

Phenology. Growth response was greatest in the very youngest plants (Cure et al., 1986; Rogers et al., 1984a) with the relative growth rate (RGR, dry matter accumulation per unit dry matter) increasing asymptotically with carbon dioxide concentration from 5 days to 2 weeks after planting. Later, the RGR remained the same for all CO_2 treatments when plants were 2 to 12 weeks old (Rogers et al., 1984a).

The relative carbon dioxide response (percent growth increase due to higher levels of CO_2) was cumulative but the rate progressively decreased while the net assimilation rate (NAR = dry matter accumulation per leaf area) in the plants exposed to high amounts of CO_2 remained above that in the control plants. Later, the dry matter accumulation for different carbon dioxide treatments was similar, causing the relative response rate to decline (Cure et al., 1986).

PHOTOSYNTHESIS

In general, researchers have found that exposing soybeans to elevated concentrations of carbon dioxide causes increases in photosynthesis on a leaf area basis (Clough et al., 1981; Finn and Brun, 1982; Rogers et al., 1983a,b; Ackerson et al., 1984; Havelka et al., 1984a; Hesketh et al., 1984; Huber et al., 1984; Peet, 1984; Valle et al., 1985a; Campbell et al., 1987; Sionit et al., 1987) or on a plant canopy basis (Ackerson et al., 1984; Rogers et al., 1984a; Jones et al., 1985a,b,c,d; Cure et al., 1986; 1987; Allen et al., 1987).

Jones et al. (1985a,b,c) conducted a series of experiments in which plants were grown for about half their growing seasons in either a high or a low level of CO_2 and then switched for a few days to the other concentration. In each case, canopy photosynthesis (net carbon exchange rate, CER) immediately responded to the new levels of carbon dioxide. In contrast, Clough et al. (1981) observed that plants grown in ambient levels of CO_2 had higher photosynthetic rates than plants grown in 1000 μL/L CO_2 when measured at either concentration.

Campbell et al. (1987) studied the photosynthetic increases in plants grown or measured at high partial pressures of CO_2. With either short- or long-term exposure, they found no increases in either the initial or total in vitro activity of the main enzyme of carbon fixation, ribulose bisphoshate carboxylase (rubisco). Vu et al. (1983, 1987) actually found decreases in these activities with exposure to high levels of carbon dioxide. While an early study reported an increase in the enzyme's regenerated substrate other than CO_2, ribulose bisphosphate (RuBP) (Vu et al., 1983), a later study by the same group found no change in concentration of this substrate on exposure to additional carbon dioxide (Campbell et al., 1987). Certainly this does not rule out different in vivo activities.

Campbell et al. searched for other bases for the photosynthetic differences seen in plants grown in high and low concentrations of CO_2. When carbon dioxide levels were high, the mesophyll cells in the palisade layer of the leaf proliferated, increasing the internal surface area for gas exchange and the number of chloroplasts for photosynthetic reactions. They also found more sinks (pods) on the plants grown in high concentrations of CO_2, which they felt would enhance assimilate demand, which in turn usually causes a rise in photosynthesis.

Valle et al. (1985a) also found reasons for the enhanced reaction. Soybeans adapted to 660 μmol CO_2/mol air and measured at seedfill utilized both light and carbon dioxide more efficiently at elevated CO_2 and through all light levels than leaflets grown at 330 μmol/mol. Binding of CO_2 to the enzyme rubisco was tighter in the plants adapted to high amounts of CO_2 than in the plants grown in ambient levels of carbon dioxide, indicating a suppression of the harmful photorespiratory reaction in the former leaflets. On the other hand, dark respiration was seen to increase in soybeans in elevated atmospheres of CO_2 (Jones et al., 1985c).

Experimental conditions. In two careful experiments, Rogers et al. (1986) and Sionit et al. (1984) placed open-top chambers randomly on preplanted fields. They found that soybean plants grown in open field soil did not respond at all in photosynthesis (mg CO_2 fixed/dm^2 h) or growth (net assimilation rate, NAR = dry matter accumulation per leaf area) to increasing levels of carbon dioxide. Their potted counterparts in the same field chambers increased photosynthetic rates along with rising levels of CO_2 just as had all other experimental plants (Sionit et al., 1984), but responded in NAR to elevated carbon dioxide concentrations only when very young (Rogers et al., 1986).

Sionit et al. (1984) felt that there was some harmful effect of confining the roots to a small volume which altered the plants' response, whereas Rogers et al. (1986) felt some stresses of the field (perhaps low nutrition) rendered the plants in open-field soil unable to respond to the CO_2 enrichment. Whichever explanation is correct, it is clear that plants in pots cannot serve as models for photosynthetic responses to high concentrations of carbon dioxide.

More puzzling are the discrepancies between these results and those of many research groups using soybean planted directly into the soil in closed-top field chambers. The latter have consistently observed photosynthetic and yield increases in soybeans exposed to rising concentrations of CO_2. The closed chambers seem to have evapotranspiration comparable to that observed in open field situations (Jones et al., 1984, 1985a, b,c,d); but at least in the case of the University of Florida SPAR units, the chambers are placed on reconstituted -- and therefore not natural -- soils, and planting soybean in predetermined locations probably affects randomization of treatments.

FEEDBACK INHIBITION

Clough et al. (1981) and Peet (1984) found rapid and continuous decreases in photosynthesis per plant in soybean plants grown in a phytotron in 1000 μL/L CO_2. This rate stayed higher than photosynthesis per plant of plants grown in 350 μL/L until senescence for Peet (1984) but not for Clough et al. (1981). Jones et al. (1985c) disagreed with the latter, based on the results of their switch experiments (see above). In contrast to suggestions that the response to carbon dioxide enrichment could show feedback inhibition, they saw a consistent positive response of soybean canopy CER to CO_2 concentration during vegetative growth, regardless of previous CO_2 treatment levels. Valle et al. (1985a) and Campbell et al. (1987) found similar results when they measured photosynthesis in soybean leaflets.

Source-sink relationships. Clough et al. (1981) observed that high-sink plants (those with a high pod:leaf ratio) had higher levels of photosynthesis per plant than low-sink plants, whether grown at ambient or high levels of CO_2. However, the dry weight of all plant parts was higher in the low-sink plants. In contrast, Peet (1984) decreased the pod:leaf ratio from 15:1 to 5:1 and saw no effect on photosynthesis/unit area. When she raised the CO_2 concentration from 350 to 1000 μL/L, the total weight and pod weight in 15:1 plants (high-sink or not sink-limited) increased. But high partial pressures of carbon dioxide had no effect on total weight or pod weight in 5:1 (sink-limited) plants (Peet, 1984). Ackerson et al. (1984) observed similar results in field-grown soybeans: plants increased their seed yields only when the elevated atmospheres of CO_2 were applied at times of high sink demand, especially at podfill. In other words, plant response to carbon dioxide enrichment during reproductive growth seemed to depend on the presence of plenty of sinks that could accept newly synthesized carbohydrates.

Carbohydrate accumulation and export. Cure et al. (1987) examined assimilate utilization in soybean plants grown in elevated atmospheres of carbon dioxide. They felt that the plants mounted a defense against feedback inhibition of photosynthesis by minimizing the buildup of photoassimilates and adjusting rates of export from the source leaves according to the strength of both sources and sinks.

Initially (within 2 days of being placed in enriched atmospheres of carbon dioxide) dry weight increases in 13-day-old vegetative soybean plants exposed to high concentrations of CO_2 were associated with accumulations of high levels of nonstructural carbohydrates in leaves and increases in specific leaf weight (weight per leaf area). After 3 days, dry weight began to increase rapidly in stems and roots, which was associated with an early increase in the estimated rate of assimilate utilization in the dark. After this point, specific leaf weight of plants grown in high partial pressures of CO_2 no longer increased relative to that of controls.

Later, assimilate utilization in the light increased as sinks, including stems and roots, began to grow. Daytime export from source leaves was controlled by sucrose biosynthesis. NAR declined in both carbon dioxide treatments but remained higher at 700 μL/L than at 350 μL/L throughout the experiment. Total leaf area of plants in carbon dioxide enrichment did not increase significantly over controls until 13 days after the start of treatment.

Cure et al. (1987) contended that dark mobilization of assimilates responded to variations in concentrations of carbohydrates in source leaves. Export of assimilates in light seemed to adjust more slowly to buildup of carbohydrates and appeared to be sink-determined, increasing only as these other organs developed throughout the plant.

The observations of Ackerson et al. (1984), Havelka et al. (1984a), and Huber et al. (1984) on older soybean plants differ slightly from those of Cure et al. on young vegetative plants (1987). Field-grown soybeans raised from 22 days after planting in 1232 μL/L CO_2 had higher levels of leaf sucrose and glucose than did control plants until the time of flower bud development, when leaf carbohydrates were depleted (Ackerson et al., 1984; Havelka et al., 1984a). Plants grown in high levels of carbon dioxide also had large pools of starch and sucrose in their leaves during seedfill, suggesting that these carbohydrates were not used for seed development. In contrast, control plants were almost devoid of sucrose and starch at plant maturity (Havelka et al., 1984a).

Huber et al. (1984) saw that plants grown in the field at 649 μL/L CO_2 had higher photosynthetic rates but rates of sucrose export and activities of sucrose phosphate synthase that were similar to control plants. Essentially all the extra carbon in plants grown in elevated partial pressures of CO_2 was partitioned into starch. Sucrose export from the leaves rose with sucrose concentration until it reached 12 mg/dm^2, after which export remained constant (Huber et al., 1984).

The average daytime content of leaf starch rose with increasing carbon dioxide concentration (Ackerson et al., 1984; Havelka et al., 1984a; Huber et al., 1984; Rogers et al. 1984b; Allen et al. 1988), from 85 g/kg dry weight at 330 μmol CO_2/mol air to 205 g/kg dry weight at 800 μmol CO_2/mol air (Allen et al., 1988). But daytime rate of starch accumulation was the same regardless of carbon dioxide concentration (0.64 g/m^2 hr at 48 days after planting; 0.29 g/m^2 hr at 69 days after planting) (Allen et al., 1988), indicating some difference in night export of starch, as was seen in cotton raised in high CO_2 levels (Kimball et al., 1985).

STOMATAL RESPONSES

Most investigators have observed that soybean plants in enriched atmospheres of carbon dioxide undergo either decreases in stomatal conductance (Rogers et al., 1983a,b, 1984b; Havelka et al., 1984a; Sionit et al., 1984) or increases in stomatal resistance (Huber et al., 1984; Jones et al., 1984, 1985b; Valle et al., 1985b). Bulk canopy resistance (stomatal resistance and boundary layer resistance, a measure of the unstirred layer of air just outside the leaf surface) at 800 μmol CO_2/mol air was 1.6 times greater than the bulk canopy resistance at 330 μmol CO_2/mol air (Jones, 1984). But Jones et al. (1985b) found total canopy resistance to transpiration was equal with different carbon dioxide treatments because the increase in stomatal resistance was offset by increased leaf area.

Rogers et al. (1984b) found a more complex situation, where high concentrations of carbon dioxide had opposite effects on stomata depending upon the water status of the soybean plants. When the plants were well-watered, stomatal conductance declined with rising CO_2, but in drought-stressed plants stomatal resistance declined with rising carbon dioxide.

TRANSPIRATION AND WATER USE

Contradictory results have been obtained with respect to transpiration and water use. Several investigators did not find differences in water use (Jones 1985a) or transpiration (Jones et al., 1985a,b; Valle et al., 1985b) with CO_2 treatment, whether plants were grown or measured at different carbon dioxide concentrations. Valle et al. (1985b) found that transpiration of leaflets acclimated to high levels of CO_2 was similar to leaflets grown in ambient concentrations of CO_2. They concluded that this occurred because enriched atmospheres of carbon dioxide caused both a rise in stomatal resistance, which lowers transpiration, and a partially offsetting rise in leaf temperature, which in turn increased the vapor pressure gradient from leaf to air, thus raising transpiration.

Others found transpiration inversely related to carbon dioxide concentration (Carlson and Bazzaz, 1980; Huber et al., 1984; Jones et al., 1985c;). Jones and coworkers (1985d), measuring transpiration over an entire season, found transpiration decreased 10% at 660 μmol CO_2/mol air compared with that at 330 μmol/mol. Water use was also seen to decline with high carbon dioxide concentration (Jones et al., 1985b; Rogers et al., 1983a). In well-watered plants, though plants grown in elevated partial pressures of CO_2 had higher leaf areas per plant, water loss per plant decreased because increasing carbon dioxide lowered the stomatal conductance (Rogers 1984b).

In one study, transpiration responded immediately to a switch in carbon dioxide level from low to high or vice-versa (Jones et al., 1985c); in another paper, Jones et al. (1985b) stated that while short-term exposure to different CO_2 treatments adequately estimated long-term canopy CER response to carbon dioxide, it didn't represent the long-term canopy transpiration response. They said this because before the switch, transpiration rates in the two treatments were essentially the same, but after the switch, plants going from enriched atmospheres to current levels of CO_2 (which plants had higher leaf area) used 36% more water, while those going the other way (which had lower leaf area) used 18% less water.

LEAF TEMPERATURES

Regardless of carbon dioxide level during adaptation (whether exposure to high concentrations of CO_2 was short- or long-term), both stomatal resistance and leaf temperature rose as carbon dioxide concentration increased. Leaf temperature of plants at double the ambient partial pressures of CO_2 was 1.5°C greater than plants at ambient levels of the gas (Valle et al., 1985b).

TEMPERATURE INTERACTIONS

Soybean plants grown in high levels of CO_2 seemed to respond positively to temperature increases within moderate limits, but there is no evidence that they will do well at temperatures above 26°C. Sionit et al. (1987) worked with three sets of day/night temperatures (18/12, 22/16, and 26/20°C) and three concentrations of CO_2 (350, 675, and 1000 μL/L). No seeds were produced at 18/12° at any carbon dioxide concentration. Both the number of seeds and the number of pods per plant increased with temperature, so that seed yield increase with high levels of carbon dioxide was greatest at highest temperatures, especially from 350 to 675 μL/L CO_2.

However, the increase in leaf net photosynthesis in response to increasing carbon dioxide concentrations was best at the intermediate temperatures. At cool temperatures, the plants had extended photosynthetic capacity (they put off senescence) but this didn't result in allocating more dry matter to the developing pods. These data might be interpreted as supportive of the Idso et al. (1987a,b) hypothesis that yield increases with high partial pressues of the gas are enhanced by high temperatures; but the highest temperatures Sionit et al. used (26/20°C) were very moderate and may be far less than those predicted by global climate change models. There is no assurance that the yields would continue to increase at daytime temperatures of 30 or 34°C. In contrast, Jones et al. (1985a) studied the photosynthetic rate (canopy CER) of soybeans grown in 330 and 800 μmol CO_2/mol air with dry-bulb temperature from 28 to 35°C. Photosynthesis was not significantly changed by variations in temperature over this range.

DROUGHT STRESS

Depriving soybean plants of adequate water seems to be the most significant influence on their reaction to increased carbon dioxide. (As mentioned above, the term "drought" is descriptive but not quantitative, and can refer to events varying in severity, duration, and stage of development at which they are applied.) Though plants grown in enriched carbon dioxide had greater growth, they had lower rates of water use which delayed and prevented the onset of severe water deficit stress under low moisture availability (Huber et al., 1984; Rogers et al., 1984b).

Water-deficit stress imposed at ambient partial pressures of CO_2 decreased soybean seed yield and final biomass. But soybean plants exposed to high concentrations of carbon dioxide and drought-stressed during their reproductive stages maintained yields higher than those of nonstressed plants at current levels of CO_2 (Jones 1985d). However, Vu et al. (1987) found the drought-stressed plants' response to extra carbon dioxide was not large enough to make up for photosynthetic declines caused by severe drought stress.

Rogers et al. (1984b) found high concentrations of CO_2 had opposite effects on stomata depending upon water status of the plants. When they were well-watered, stomatal conductance declined with rising carbon dioxide, but in water-limited plants stomatal resistance declined with rising CO_2.

WATER-USE EFFICIENCY

In all cases reported, water-use efficiency (WUE) of soybeans rose with atmospheric enrichment of carbon dioxide (Carlson and Bazzaz, 1980; Rogers et al., 1983b; Havelka et al., 1984a; Huber et al., 1984; Jones et al., 1984; Valle et al., 1985b). In a typical example, in leaves adapted to 660 μmol CO_2/mol air, WUE (measured as CER/transpiration) was twice as high as the WUE of leaves adapted to and measured at 330 μmol/mol, chiefly because of a twofold rise in CER at 660 μmol/mol (Valle et al., 1985b). WUE does not increase with increasing temperatures, because of the temperature-driven increase in transpiration (Jones et al., 1985a).

NITROGEN FIXATION AND NUTRIENTS

Despite its enhancement of photosynthesis and therefore of available carbohydrates, carbon dioxide enrichment appeared to have little short-term effect on nitrogen fixation as measured by total or specific root nodule activity. Dry weight of roots and nodules and total nodule activity increased only after 16 days of treatment, long after extra carbon had been partitioned to shoot parts. Specific nodule activity was never enhanced by high levels of CO_2, indicating that nodule activity responded to extra CO_2 only as a consequence of the general growth respose of the plant. Nodule activity was not limited by photosynthesis at current CO_2 concentrations, but by partitioning of photosynthate (Finn and Brun, 1982).

Soybean plants grown at 675 ppm CO_2 overcame a low nutrient level (1/8-strength Hoagland's solution) to produce more biomass, more total seed yield, more pods, and larger weight per seed than plants grown at 350 ppm and half-strength Hoagland's solution (Sionit, 1983).

Plants took better advantage of high partial pressures of carbon dioxide (growth response as NAR was greatest) when nutrients such as nitrogen and phosphorus were at optimal levels. Conversely, at early podfill they also used nitrogen and phosphorus most efficiently (add g dry weight per mg nitrogen or P) at higher levels of CO_2. The same levels of phosphorus nutrition were optimal for both plants grown in ambient levels of CO_2 (350 ppm) and those grown in a high CO_2 concentration (700 ppm); but plants grown at 700 ppm tended to have lower leaf phosphorus concentrations. Soybeans at 700 ppm CO_2 required more nitrogen for optimum growth. Plants grown in enriched atmospheres of carbon dioxide but provided with inadequate concentrations of nitrogen or phosphorus increased their uptake of those nutrients, but their growth declined with the concentration of these nutrients (Cure et al., 1986).

INSECT FEEDING

Feeding rates of soybean looper larvae , an insect herbivore, increased 30% on plants grown in 650 μL/L CO_2 from those grown at 350 μL/L. These feeding increases were related to declines in leaf content of the water and nitrogen, indicating that the insects fed more heavily to make up for the poorer food quality (from their point of view!) of the plants grown in high levels of CO_2 (Lincoln et al., 1986). (The previously noted increases in leaf starch content would create apparent percentage decreases in leaf nitrogen, water, and protein.) At 800 μmol CO_2/mol air, Allen et al. (1988) saw a 45% increase in total plant nitrogen in seed and senescent tissues at season's end. These reports do not necessarily contradict each other; for Lincoln et al. (1986) were measuring photosynthesizing leaf tissue; and if the carbon-based biomass of the soybean rose more than 45%, there could be a concomitant rise in the C:N ratio, as was seen by Lincoln et al. (1986).

CHAPTER 4

WHEAT

Wheat (Triticum aestivum L.) is the most important food crop in the world, planted on a greater area and feeding even more people than rice (Coulman, 1987; Roecklein and Leung, 1987; Starling, 1987). Originally from Afghanistan, wheat is grown on every continent. Major production comes from Asia; the Soviet Union, which raises 16% of the world's crop (about 80 million tons in 1983); the United States, which produced 66 million metric tons in 1983, half of which was exported; and from Canada, Australia, and Argentina (Coulman, 1987; Roecklein and Leung, 1987).

The high gluten content of wheat permits its dough to adhere and increase in volume during baking, rendering it the most suitable grain for bread. Other wheat products include all types of baked goods, pasta, breakfast cereals, gravy, alcohol, starch, and straw for animal bedding (Roecklein and Leung, 1987; Starling, 1987).

Wheat grown in North America falls into two categories. Obligate winter wheat is planted in autumn, must undergo a vernalization period of low temperatures before it will flower and produce seed, and is harvested in early to midsummer. Winter wheat descended from Ukranian cultivars brought in the 1880's accounts for two-thirds of the U.S. crop, and grows in the Great Plains from Texas to North Dakota, the Midwest, the Northwest, and parts of the East Coast. Since these plants frequently encounter desiccating cold, ice, and snow, they have different tolerance to environmental conditions at various stages than do spring wheats.

Several species and types of spring wheat are planted in spring and grown in summer in the far North (Montana, the Dakotas, Wyoming, and western Canada), California, and parts of the East, and grown in winter in the far Southwest and Mexico. The response of wheat to high carbon dioxide concentration depends in part upon which of these two types it is. However, results for the two groups with respect to yield, phenology, and photosynthesis are similar, so findings for most of these will be grouped together.

YIELD

Biomass accumulation and vegetative growth. High carbon dioxide concentrations (450, 485, 660, 675, 825, and 1000 μL/L) cause increases in total dry weight both at maturity (Gifford, 1977; Sionit et al., 1980, 1981a,b; Havelka et al., 1984b; Chaudhuri et al., 1987) and incrementally thoughout the season (Sionit et al., 1981a; Gifford et al., 1985; Schonfeld, 1987). Winter wheat exhibited dry weight increases in leaves, stems, and tillers (Havelka et al., 1984b; Marc and Gifford, 1984; Chaudhuri et al., 1987). Both types of wheat showed increased stem height (Sionit et al., 1981b; Chaudhuri et al., 1986, 1987).

Leaf area. Both types also developed greater total leaf area in enriched CO_2 concentrations (Sionit et al., 1981b; Marc and Gifford, 1984; Chaudhuri et al., 1987; Wall and Baker, 1987). Wall and Baker (1987) surmised that these vegetative changes gave the plants a more favorable canopy structure for light interception. In spring wheat, this leaf area increase was accomplished by enlarging leaf length and width, but not number of leaves (Wall and Baker, 1987).

However, in winter wheat both size (Chaudhuri et al., 1986) and number (Chaudhuri et al., 1986; Schonfeld, 1987) of leaves rose with amount of carbon dioxide, so that by 20 days after CO_2 application began again in early spring (March 8, 1986), leaf area had doubled; after 40 days, the number of leaves had doubled (Chaudhuri et al., 1986, 1987).

Roots. Field-rhizotron-grown winter wheat plants responded to increased CO_2 with greater root weight (Chaudhuri et al., 1986) and root length density (Chaudhuri et al., 1987), which usually helps plants enhance their water absorption.

Assimilate partitioning. When plants were well-watered, spring wheat plants grown in a phytotron showed an increase in their root-shoot ratio (Sionit et al., 1981b), but in winter wheat the percent increase in shoot growth was higher than the percent increase in root growth (Chaudhuri et al., 1986).

In spring wheat there was no change in the ratio of leaf area or leaf dry weight to total dry weight of the plant; or of leaf area to total leaf dry weight (Sionit et al., 1981b) so all vegetative components seemed to increase in a coordinated fashion. In contrast, in winter wheat specific leaf weight (weight per unit area) increases with increasing carbon dioxide (Havelka et al., 1984b; Schonfeld, 1987). The specific leaf weight increase could have been accomplished by an increase in photosynthesizing cells, by an increase in the amount of carbohydrates, or by both.

Grain yield and yield components. Grain yield increased with elevated carbon dioxide concentration (Gifford 1977, 1979; Sionit et al., 1980, 1981a,b; Havelka et al., 1984b; Chaudhuri et al., 1986, 1987; Wall and Baker, 1987). Among changes seen in the yield components were increased numbers of tillers (Gifford, 1977; Sionit et al., 1980, 1981b; Marc and Gifford, 1984; Chaudhuri et al., 1986, 1987; Schonfeld, 1987; Wall and Baker, 1987), which doubled in at least one case (Chaudhuri et al., 1986); faster rate of tiller emergence (Gifford, 1977; Sionit et al., 1981b); and reduced tiller abortion (Havelka et al., 1984b; Wall and Baker, 1987). (The number of tillers produced determines the maximum number of heads.)

Increases were seen in the number of heads per m^2 (Gifford, 1977; Havelka et al., 1984b), number of grains (Gifford, 1979; Havelka et al., 1984b; Sionit et al., 1980, 1981a,b), mass of grains (Sionit et al., 1980, 1981a,b), or all of these yield components (Chaudhuri et al., 1987, 1986) through effects on phenology, photosynthesis, and water relations. CO_2 enrichment caused an increase in the number of tillers which actually produced heads (Gifford 1977; Sionit et al., 1981c; Havelka et al., 1984b), but not in the number of spikelets per head (Sionit et al., 1981c).

Havelka et al. (1984b) found no effect of carbon dioxide concentration on harvest index (ratio of grain yield to total biomass), but Chaudhuri et al. (1987) saw greater effects on winter wheat kernel weight than on roots and phytomass. Wheat yields were most affected by high concentrations of CO_2 during the period when the seed number was determined (Havelka et al., 1984b).

Phenology. Gifford (1977) found rate of wheat leaf emergence unchanged by carbon dioxide concentration, but higher levels of CO_2 directly affected flowering, including advancing floral initiation (Marc and Gifford, 1984). However, carbon dioxide enrichment was observed to both accelerate development of the immature heads (Havelka et al., 1984b) and to retard the rate of differentiation of the primordial inflorescence (Marc and Gifford, 1984).

PHOTOSYNTHESIS

Net assimilation rate rose with increasing carbon dioxide in spring wheat (Wall and Baker, 1987, Sionit et al., 1981b) and on a per chlorophyll basis in winter wheat (Azcon-Bieto, 1983; Gifford et al., 1985; Schonfeld, 1987). Gifford (1977) observed an increase in whole-plant net photosynthesis during CO_2 enrichment, but not in the maximum rate of flag leaf photosynthesis; in contrast, Havelka et al. (1984b) saw a 50% increase in apparent photosynthesis of the flag leaf (the leaf just under the head, whose photosynthesis has great effect on grain yield). Plants in a relatively low-light environment responded more to elevated partial pressures of CO_2 than did those in higher light (Gifford, 1977).

FEEDBACK INHIBITION

Carbohydrate accumulation. More reduced carbons were available to wheat grown in elevated atmospheres of CO_2 (Sionit et al., 1980, 1981d; Azcon-Bieto, 1983; Havelka et al., 1984b; Chaudhuri et al., 1986, 1987; Wall and Baker, 1987), including a doubling of flag leaf sucrose and starch concentrations prior to seed growth (Havelka et al., 1984b). The carbohydrate accumulation in leaves was associated with decreased net CO_2 uptake, which recovered after a short dark period during which carbohydrates were removed from the leaves, indicating feedback inhibition (Azcon-Bieto, 1983). Water-soluble carbohydrates in the whole plant, stem, and leaf at harvest were higher (Havelka et al., 1984b; Chaudhuri et al., 1987), but roots did not accumulate sugars (Gifford et al., 1985) in plants raised in enriched-CO_2 environments.

Source-sink relationships. High flag leaf sucrose and starch concentrations fell rapidly to control levels with the onset of seed growth, suggesting a rapid mobilization of photosynthate to the head and developing seeds (Havelka et al., 1984b). Translocation appeared essential for maintenance of a high photosynthetic rate. CO_2 assimilation declined markedly when treatments that lowered the rate of translocation from mature wheat source leaves (e.g., lower temperatures or chilling the base of the leaf) were applied to plants exposed to 340, 700, or 825 μbars CO_2 (Azcon-Bieto, 1983).

Photosynthetic regulation. The rate of net CO_2 assimilation fell more sharply with time in wheat plants treated with high levels of carbon dioxide than in control plants, regardless of temperature (Azcon-Bieto, 1983). Photosynthetic efficiency (assimilation on a leaf area basis as a function of internal carbon dioxide concentration, c_i) was similar for plants grown in ambient and 700 μL/L CO_2 (Schonfeld, 1987), or actually lower in leaves exposed to enriched atmospheres of carbon dioxide (Azcon-Bieto, 1983).

OTHER CARBON-EXCHANGE REACTIONS

Dark respiration. Wheat grown in 590 μL/L CO_2 lost only half as much carbon dioxide in whole-plant night respiration as plants grown in 340 μL/L CO_2. Respiration from young wheat roots was reduced as much as 45% by exposure to 680 μL/L CO_2. The proportion of respiration cycling through the wasteful alternative pathway declined more than did respiration through the cytochrome pathway, leading to much greater retention of carbon under CO_2 enrichment (Gifford et al., 1985).

Photorespiration. Wheat leaves at moderate temperatures (25°C) and high carbon dioxide concentrations showed reduced photorespiration (Kobza and Edwards, 1987), but at higher temperatures (35, 40, or 45°C) photorespiration caused a significant reduction in photosynthesis whether carbon dioxide concentrations were ambient or elevated (Azcon-Bieto, 1983; Kobza and Edwards, 1987). With rising temperatures, the activation state of rubisco changed so carboxylation activity was reduced, and the oxygen/carbon dioxide solubility ratio rose. These changes caused an increase in photorespiratory loss of carbon dioxide relative to carbon dioxide fixation that could not be eliminated by the greater amounts of CO_2 in the air (Azcon-Bieto, 1983; Kobza and Edwards, 1987). Thus it appears wheat photorespiration will increase with climate change.

STOMATAL RESPONSES

In well-watered winter wheat, a high level of CO_2 increased stomatal resistance (Havelka et al., 1984b; Chaudhuri et al. 1986), or decreased stomatal conductance (Azcon-Bieto, 1983) which tended to prevent water loss. However, in drought-stressed plants, Chaudhuri et al. (1986) observed no difference in stomatal resistance based on CO_2 treatment.

TRANSPIRATION

Chaudhuri et al. (1986) also found that enriched atmospheres of CO_2 increased total transpiration to two times that of ambient. They suggested that this may be due to greater phytomass per ground area, with the plants in high carbon dioxide levels growing faster early in the season and covering the ground with more transpiring plants. Later in the season as the ground was covered more fully by both CO_2 treatments, the CO_2

effect on transpiration declined. Another explanation for the rise in transpiration could be the higher canopy (leaf) temperature at high carbon dioxide concentration (see below).

LEAF TEMPERATURE

Among the most significant findings about high levels of carbon dioxide and winter wheat are studies of leaf/canopy temperatures by Chaudhuri et al. (1986, 1987). Leaf temperatures of plants grown in enriched atmospheres of CO_2 were higher than those grown at current levels of CO_2 (Chaudhuri et al., 1987). Mean canopy minus air temperatures for plants from high-CO_2 treatments averaged 1.0 to 1.5°C greater than for plants from ambient atmospheres of CO_2.

This difference was more pronounced (plants from high concentrations of CO_2 were 2.8°C hotter than ambient-grown counterparts) when air temperature was "high" (27.7°C, not usually considered a high temperature). Between 330 and 825 μL/L CO_2, the average difference was 3°C. This was true whether the wheat plants were well-watered or drought-stressed.

The rise in leaf temperatures seen by Chaudhuri et al. (1986, 1987), when combined with warmer air temperatures, could lead to biochemically-based inhibition of growth and yield as sensitive enzymes react to potentially denaturing conditions, as seen when Kobza and Edwards (1987) externally manipulated the leaf temperature as well as the CO_2 concentration (see photorespiration, above, and temperature interactions, below). These high leaf temperatures could create damage too great to be offset by any CO_2-induced yield increase.

TEMPERATURE INTERACTIONS

Of similar importance are the findings of Wall and Baker regarding temperature interactions in spring wheat (1987). This preliminary report (abstract only) of their study indicates that they grew plants in outdoor chambers with day/night temperature of 16/8°, 23/15°, or 30/22°C. Plants grew best at the highest CO_2 levels and the lowest temperatures. Higher temperatures caused fewer tillers to form and smaller leaves to form on those tillers.

As mentioned above, photorespiration increased with temperature, even at 800 μL/L CO_2, reducing net photosynthesis in wheat leaves exposed to temperatures above 25°C. Photosynthetic inhibition at high temperatures was associated with irreversible damage to enzymes and electron transport, and uncoupling of photophosphorylation (Azcon-Bieto, 1983; Kobza and Edwards, 1987). As temperatures rose from 15° to 45°C, extractable activity of rubisco and fructose 1,6-bisphosphatase decreased (the former by 50%), and the thylakoid membrane showed symptoms of damage (Kobza and Edwards, 1987). Clearly the predicted global warming could harm wheat plants despite the presence of additional photosynthetic substrate.

Experimental conditions. Chaudhuri et al. (1987) also discussed technical problems of temperature inside their chambers. They found that the canopy temperature of any treatment was a few degrees hotter than the open-air temperature (in contrast to the usual finding of well-watered plants being cooler than the surrounding air), probably due to a 2 to 3°C higher air temperature inside the chambers than in the open field. This latter difference was greater at night and at cool temperatures -- up to 8°C warmer in the chambers at those times. Although this may render their data inaccurate representatives of current conditions, it means that their experiments unwittingly represent more closely the high temperatures expected with a high CO_2-induced climate change.

DROUGHT STRESS

The most pronounced differences between spring wheats and winter wheats responding to added CO_2 are found in interactions between drought stress and high carbon dioxide concentration. Again, this may be because "drought" and "water deficit" are descriptive terms and are difficult to quantify or compare across experiments. Well-watered wheat plants of both types make more carbohydrates when grown in high levels of CO_2 (Sionit et al., 1980, 1981d; Azcon-Bieto, 1983; Havelka et al., 1984b; Chaudhuri et al., 1986, 1987; Wall and Baker, 1987), which might enable them to cope better with subsequent drought cycles.

Spring wheat. Water deficits applied to spring and winter wheat yielded different results. Although spring wheat plants at both high and low CO_2 levels produced fewer and smaller grains when drought-stressed, plants at high concentrations of CO_2 produced more stems and heads than did plants at ambient levels. In fact, drought-stressed plants in high partial pressures of CO_2 had grain yields and total dry weight equal to that of unstressed plants at current CO_2 levels (Sionit et al., 1980).

Sionit and coworkers suggested that CO_2 enrichment increases the yield potential of water-stressed wheat plants, probably by increasing the concentration of solutes in leaves and thereby enhancing osmotic adjustment, which helps plants cope with drought (Sionit et al., 1981d, 1980). Since all their work was conducted with plants grown in pots in controlled indoor environments, the evapotranspiration and thus many gas exchange phenomena, including photosynthesis and conductance, may not be indicative of those in high-light and windy field conditions with unrestricted root zones and variable field soils. Thus these results need to be interpreted with caution before extrapolating to field predictions for spring wheat.

Winter wheat. The results of Sionit and coworkers are also in contrast to findings for drought-stressed winter wheat. In all cases drought stress lowered winter wheat yield so much that even the highest CO_2 levels (825 μL/L) did not restore plant parameters to the levels achieved by nonstressed plants at ambient CO_2. This applied to grain yields (Chaudhuri et al., 1987, 1986), photosynthesis (Schonfeld, 1987), and biomass (Schonfeld, 1987, Chaudhuri et al., 1987, 1986). Grain yield for nonstressed plants grown at 825 μL/L CO_2 was 30% (1986) or 60% (1985) higher than plants grown at 330 μL/L. Yield increases for drought-stressed plants furnished with high carbon dioxide concentrations were 63% (1986) or 55% (1985) more than yields of plants grown in current CO_2 levels. Winter wheat plants do not seem to be able to use increased levels of carbon dioxide to make up for the effect of water stress on yield.

From a somewhat different perspective, Gifford (1979) raised wheat in a phytotron at four different levels of growth-restricting water supply. Plants given less water had a smaller absolute yield response to CO_2 enrichment (590 μL/L) but a greater response relative to control yields. In an extremely arid treatment, plants in ambient concentrations of CO_2 made no grain, but those at a high concentration did make grain.

As mentioned above, Chaudhuri et al. (1986) also found that stomatal response of plants to enriched atmospheres of carbon dioxide was dependent upon their water status. In well-watered plants, high concentrations of CO_2 increased stomatal resistance, but in drought-stressed plants, they observed no difference in stomatal resistance based on CO_2 treatment.

WATER-USE EFFICIENCY

Raising the carbon dioxide level also affected the WUE of winter wheat plants. Under high partial pressures of CO_2, less water was needed to make a gram of kernel than at ambient CO_2 (Chaudhuri et al., 1987, 1986). Drought-stressed plants given enriched atmospheres of CO_2 needed similar amounts of water to nonstressed plants in ambient levels of CO_2 to produce kernel mass. Nonstressed plants at 825 μL/L CO_2 used 14% less water to make one gram of kernel than at ambient concentrations of CO_2; drought stressed plants used 23% less.

Rose

NUTRITION

Sionit and coworkers (1981a) also investigated interaction of CO_2 enrichment of the air and mineral nutrition. In addition to increasing total dry weight, seed weight, and seed number from those seen in control plants at each nutrient level, high levels of CO_2 enabled plants to use higher concentrations of nutrients without the inhibition seen at ambient levels of CO_2. Elevated carbon dioxide concentration was seen to increase the grain protein of well-watered winter wheat 35% by Chaudhuri et al. (1986), but no effect of CO_2 enrichment on grain protein was observed by Havelka et al. (1984b).

CHAPTER 5

COTTON

Cotton (Gossypium hirsutum L.) accounts for 90% of the world's production of fiber and is the second most important oilseed crop as well (Coulman, 1987; Roecklein and Leung, 1987; Wilcox and Leffel, 1987). This small perennial shrub has been cultivated in both the Old and New World for at least 45 centuries (Lee, 1987; Roecklein and Leung, 1987). The largest producers are the U.S.A., where it grows all across the southern states from North Carolina to California; the Soviet Union; Turkey; and the People's Republic of China. But its high-temperature adaptation also makes it an important product in many Third World countries such as Egypt, El Salvador, India, and Mexico (Coulman, 1987; Roecklein and Leung, 1987).

YIELD

Biomass accumulation. Cotton plants exposed to 500 and 650 μL CO_2/L air in open-top field chambers increased their total dry weight 40 and 51% more than plants at ambient CO_2 (Kimball et al., 1983, 1984, 1985; Idso et al., 1987b); plants grown in a phytotron at 650 and 1000 μL/L had dry weight 72 and 115% higher than control plants, respectively (DeLucia et al., 1985). DeLucia et al. (1985) found dry weight increase was highest in leaves, as treatment with high levels of CO_2 caused leaf area to rise (Kimball et al., 1984).

Economic yield. Cotton yield can be expressed as seed cotton yield (lint and seeds) or lint yield. The field-grown plants cited above averaged seed cotton yield increases of 70% when exposed to two times the ambient CO_2 concentration over four years of experiments by Kimball et al. (1986, 1985, 1984, 1983). When plants were nitrogen fertilized, the seed cotton yield increase due to CO_2 enrichment was 48%; plants with no added nitrogen showed a 70% increase due to increasing CO_2 (Kimball et al., 1986). In these chambers, lint yield of plants exposed to 500 and 650 μL/L increased 31 and 46% (Kimball et al. 1983).

These are among the largest yield responses to high concentrations of carbon dioxide of any species so far investigated. Some reasons for this may be the following: (1) Cotton has an indeterminant life cycle and can keep producing flowers and fruits as long as the weather is favorable. (2) Cotton has a much higher saturation point for CO_2 than most other agricultural crops (Breen et al., 1986), and therefore can make use of all the extra carbon dioxide it is given. (3) At least in some cases, cotton does not close its stomata in response to carbon dioxide enrichment, enabling it to keep photosynthesizing without a stomatal inhibition (Radin et al., 1987). (4) Cotton is extremely heat-tolerant. Growing at high temperatures may help it avoid feedback inhibition, and its emzymes may not suffer the limitations other crops undergo at high temperatures (Idso et al., 1987a, 1987b). However, Perry et al. (1983) found that at 40°C, cotton photorespiratory losses equaled 50% of the carbon dioxide fixed in net photosynthesis.

Yield components. Exposure to enriched atmospheres of carbon dioxide appears to affect seed cotton and lint yield in part by increasing the number of flowers (Kimball et al., 1986, 1985, 1984, 1983), without much effect on boll retention (Kimball et al., 1985, 1984, 1983), seed index, harvest index (Kimball et al., 1985, 1984), percent lint per boll or seed size (Kimball et al., 1984).

Phenology. However, high CO_2 concentration affects the life cycle of flowering, boll-loading, and vegetative growth which cotton plants pass through, with less time between phases of the life cycle (Kimball et al., 1986). This renders the response to elevated CO_2 a function of the phase of the fruiting cycle plants are in when the season ends and therefore of the length of the season.

PHOTOSYNTHESIS

With doubled carbon dioxide concentration, leaf net photosynthesis at midseason was elevated 51 to 77% (Kimball et al., 1986, 1985, 1984, Radin et al., 1987). This substantial rise in net photosynthesis was still not large enough to account for cotton yield increases seen with elevated carbon dioxide concentration, indicating an effect of CO_2 on phenology, yield components (such as the number of flowers, mentioned above), or some other influence on growth, such as the leaf area increase seen by Idso et al. (1987b).

Phenology. At ambient levels of carbon dioxide, field-grown cotton plants did not change photosynthetic rates over the season. But when photosynthesis on these plants was measured at very high CO_2 levels, plants showed a hyperbolic curve in photosynthetic capacity over the season. Shape of the response curve to carbon dioxide concentration was dependent upon stage of growth (Breen et al., 1986); high concentrations of CO_2 increased net photosynthesis by 51% at midseason, but only 37% late in the season (Kimball et al., 1986). Photosynthesis at midseason was not saturated until the carbon dioxide concentration reached 3000 cm^3/m^3 (Breen et al., 1986; Hesketh et al., 1984).

Photosynthetic capacity. Studies by various investigators have yielded different results concerning whether or not cotton photosynthetic capacity, also called photosynthetic efficiency (assimilation rate per internal carbon dioxide concentration, c_i) declines with prolonged exposure to high levels of CO_2. Radin et al. (1987) and Kimball et al. (1985) working in Arizona found photosynthetic efficiency for well-watered field-grown cotton plants was linear over a wide range of c_i's, to at least a concentration of 700 $\mu L/L$. This phenomenon occurred in plants grown at 350 or 650 $\mu L/L$ CO_2, i.e., it was unchanged by elevated carbon dioxide concentration.

Radin et al. (1987) also estimated that c_i was at least 85% of atmospheric carbon dioxide concentration in both ambient and enriched CO_2 conditions. The Arizona group found that plants grown in high amounts of carbon dioxide in their outdoor open-top chambers experienced no decline in photosynthetic capacity, ie., no inhibition due to acclimation to high partial pressures of CO_2, until very late in the season (September) when temperatures dropped somewhat (Kimball et al., 1985; Radin et al., 1987).

However, the group working at the Duke phytotron (DeLucia et al., 1985; Sasek et al., 1985) found that cotton plants grown in high carbon dioxide concentrations (675 or 1000 $\mu L/L$) did have a diminished photosynthetic capacity when measured at 675 and 1000 $\mu L/L$ CO_2, and even at an ambient concentration, 350 $\mu L/L$.

FEEDBACK INHIBITION

This drop in photosynthetic capacity after growth in high levels of CO_2 was correlated with a high internal (nonstomatal) resistance to carbon assimilation and declines in chlorophyll content and changes in the chlorophyll a/chlorophyll b ratio (DeLucia et al., 1985).

Carbohydrate accumulation. Kimball et al. (1985) found that concentrations of leaf-soluble carbohydrates (glucose, fructose, and sucrose) were unaltered by exposure to 650 μL CO_2/L. But they observed that cotton plants grown in that level of CO_2 had starch concentrations two to five times the concentration in leaves grown in ambient carbon dioxide concentration (Radin et al., 1987; Kimball et al., 1986, 1985). Early morning minima of starch concentrations were most strongly affected by CO_2 enrichment, causing Kimball et al. (1985) to surmise that starch was not being completely broken down at night. DeLucia et al. (1985) also observed very high concentrations of carbohydrates, especially starch.

DeLucia et al. (1985) suggested that high carbohydrate accumulation may have limited photosynthesis by feedback inhibition or even physical damage to chloroplasts, which were crowded with starch grains. Sasek et al. (1985) reported that both photosynthetic inhibition and starch buildup in plants grown at 675 or 1000 $\mu L/L$ CO_2 were reversed upon placing them in an ambient level of CO_2 (350 $\mu L/L$). In order to rule out effects of stomatal changes, they calculated photosynthetic efficiency (moles CO_2 fixed m^{-2} s^{-1} $mole^{-1}$ c_i) and found that it, like net photosynthesis, recovered 3 to 5 days after being placed in the lower carbon dioxide concentration.

Experimental conditions. This apparent discrepancy in results concerning feedback inhibition of photosynthesis may be due to several differences in methodology between the two groups. Since the Duke group (DeLucia et al., 1985, and Sasek et al., 1985) did their work in a phytotron, it might be suspected that the light intensity would be lower than that obtained by the Phoenix researchers (Kimball et al., 1983, 1984, 1985, 1986; Idso et al., 1987a,b; Radin et al., 1987) growing plants outside in sunny Arizona. However, the light level measured by Sasek et al. (1985) is almost identical to that measured by Radin et al. (1987). Alternatively, the phytotron plants were grown in pots, which method is known to affect root growth and may have affected (inhibited) translocation of carbohydrates.

TEMPERATURE INTERACTIONS

The cause of the different results concerning feedback inhibition may be the differences in growth temperatures used by the two research groups. DeLucia et al. (1985) and Sasek et al. (1985) used day/night temperatures of 26/20°C (in a thermo- and photoperiod of 12h/12h, a short day for a summer crop). The Arizona group's average maximum daytime temperatures were 45.5°C in July, 43.8°C in August, and 38.5°C in September, the latter being the one time feedback inhibition was observed in Phoenix. Radin et al. (1987) ascribe this inhibition to the drop in temperature.

The Phoenix group has a theory based on observations of five different species, including cotton at various natural, uncontrolled (but generally very hot) temperatures, that plant response to elevated atmospheres of CO_2 is dependent upon temperature. At temperatures <12°C, plants experienced a negative yield response; at 19°C, plants yielded about the same in high carbon dioxide concentration as at ambient (but cotton was not grown at either of those lower temperatures). At 34°C, plants averaged 130% greater yields when amounts of carbon dioxide were doubled, and cotton seemed to respond positively to even higher temperatures (Kimball et al., 1985, 1986; Idso et al., 1987a,b; Radin et al., 1987).

Possibly cotton had such a good yield response to CO_2 enrichment because higher rates of enzyme activity at high temperatures speeded up metabolism, including respiration and translocation, enough to eliminate any dysfunctional carbohydrates clogging up the system and inhibiting photosynthesis. But at the much lower temperatures used by the Duke researchers, photosynthesis could have created many more new carbohydrates than the other plant processes could use. Sasek et al. (1985) suggested that their reversal experiments indicate if strong sinks (such as more flowers, fruits, stems, or roots) appeared, starch could decrease and photosynthesis recover during periods of high photosynthate demand, even under continuous high concentrations of CO_2.

However, in the Arizona field experiments, cotton temperatures were not controlled, and the plants were aging as the season progressed and the temperatures dropped. Considering the changes in photosynthetic response to high partial pressures of CO_2 according to stage of development mentioned above (Radin et al., 1987; Breen et al., 1986; Kimball et al., 1986, 1985) one cannot be sure that this decline in photosynthesis with time is due to temperature, senescence, or yet another factor that is also changing with the season. Experiments done at externally controlled temperatures intermediate between the two groups (e.g. 35/25°C) and with thermoperiod and photoperiod typical of southern temperate summers would help sort out these influences.

STOMATAL RESPONSES

There is contradiction in the published experimental results on the effect of enhanced carbon dioxide concentrations on cotton stomata. One report (Kimball et al., 1985) even found opposite results with the same measuring device: stomatal resistance dropped 47% in well-watered and 69% in droughted plants exposed to high amounts of CO_2, but that stomatal conductance is unaffected (not reduced) by the same conditions. Since the two measures, stomatal resistance and stomatal conductance, are reciprocals of each other, if one rises the other should fall. Other groups found that added CO_2 treatments increased stomatal resistance (Kimball et al., 1983); or did not affect stomatal resistance when plants were well watered (Kimball et al., 1984, DeLucia et al., 1985), but increased stomatal resistance if plants were drought stressed (Kimball et al., 1984). Carbon dioxide enrichment has also been reported as not affecting the high stomatal conductance seen at midseason (Radin et al., 1987); or decreasing stomatal conductance slightly (11%) at midseason but more (25%) later in the season

(Kimball et al., 1986). In this latter case, a sharp drop in stomatal conductance late in the season was larger than any treatment differences. The decline was attributed to falling temperatures, which would cause less water to evaporate from the stomata; or to lower relative humidity, which would increase evaporative demand and might therefore induce stomatal closure.

The recent work of Idso (1987) and Idso and Allen (1988) might explain these discrepancies as artifacts of porometry. Or perhaps the answer is found in Sasek et al. (1985), who observed that stomatal function seems to adjust to high concentration of carbon dioxide over time. Plants in ambient CO_2 started out with higher conductance, which gradually fell (stomatal resistance increased) over time; plants in 1000 μL/L CO_2 started out with lower conductance, which gradually rose (stomatal resistance decreased) over time. Therefore, the level of conductance in the two treatments approached each other as the season progressed, one of many instances of plants reacting to environmental change by homeostatically tending towards core metabolic levels. If plants were switched from very high levels of CO_2 to ambient levels, conductance rose more quickly to previous levels (Sasek et al., 1985).

Another explanation is that stomatal apertures are controlled by a number of plant factors, such as leaf temperature, presence of abscisic acid in the extracellular fluid, water status of the leaf, and concentration of solutes; and environmental factors, including humidity, air temperature, carbon dioxide concentration, light, and available water in the soil. Obviously carbon dioxide concentration is just one of many influences on stomata, and in many instances, it may not be the most important or controlling factor.

The Arizona research group, who generally did not see declines in stomatal conductance in plants exposed to high carbon dioxide concentrations (Radin et al., 1987, Kimball et al., 1986, 1985), felt that this maintenance of open stomata was perhaps the reason why cotton showed a greater positive yield response to increased CO_2, with a correlation between stomatal conductance and photosynthetic capacity. They showed that plants grown in high amounts of CO_2 (Radin et al., 1987, Kimball et al., 1986) were also more reponsive to injections of ABA, which causes stomatal closure. Finally, they observed a 10% increase in the number of stomata/leaf area with high CO_2 levels.

TRANSPIRATION, WATER USE, AND WATER-USE EFFICIENCY

Since plants grown in high partial pressures of carbon dioxide had greater leaf area, in some cases their transpiration and water use per unit land area were higher, which caused the soil to be more depleted (Kimball et al., 1985). Higher leaf temperature of those plants also raised transpiration/ground area. This was counteracted by the increasing stomatal resistance (decreasing conductance), seen in at least some cases, which decreased transpiration per leaf area. In well-watered cotton plants exposed to double the current concentration of CO_2, transpiration declined 7.3% (Kimball et al., 1985; Idso et al., 1987a,b). Relative water content of the leaves decreased with increasing levels of CO_2 five or six days after irrigation (Kimball et al., 1985).

Results concerning the effect of high partial pressures of CO_2 on water use are inconclusive, whether measured with lysimeter (a device to weigh both soil and plants) or neutron probe (a device that bounces neutrons off soil water molecules) (Kimball et al., 1984, 1983). However, the large yield increases with a small change in water use translated into large increases in water-use efficiency.

LEAF TEMPERATURE

Despite the differences in experimental results with stomata, there is agreement that increases in leaf temperature (which are generally secondary effects of stomatal closure) occur when high concentrations of CO_2 are administered to cotton plants (and all other species studied). Kimball et al. (1984) found that well-watered plants exposed to high levels of CO_2 under humid conditions (vapor pressure deficit = 1 kPa) had leaf temperatures within 1°C of leaf temperatures of ambient-grown plants. As air became drier (vapor pressure deficit = 4 kPa), a doubling of carbon dioxide concentration caused leaf temperatures to increase by about 2°C.

They point out that "leaf temperature data were somewhat in conflict with stomatal resistance data," but since there were many more temperature data, the researchers concluded the latter data were probably more reliable.

Leaf temperature increases of about 1° with carbon dioxide concentrations in the 600-650 μL/L range were also found in other years (Kimball et al., 1983, 1985, 1986; Idso et al., 1987a,b). Idso et al. (1987a,b) felt this leaf temperature rise, which caused plant transpiration to fall, was the key to cotton yield increases and developed a formula for prediction of the latter from the former.

DROUGHT STRESS

Drought stress and yield. CO_2-enrichment effects on water-limited cotton are dramatic. Cotton plants exposed to high levels of CO_2 achieved yield increases that overwhelmed any yield reductions due to drought stress (Kimball et al., 1986). Raising the concentration of CO_2 from ambient to 650 ppm increased the seed cotton yield of water-limited plants from 476 to 717 g/m^2 (51%) when no nitrogen was added, and from 449 to 763 (70%) when nitrogen fertilized. This lifted the yields even above those of the well-watered plants growing in 330 ppm CO_2, which were 557 (N-) and 658 (N+) (Kimball et al., 1986). Kimball et al. (1985) found that seed yield was increased even more, to 104% of ambient levels, by placing plants in enriched atmospheres of CO_2, and that total dry weight rose 71%.

However, the water-deficit stress in these experiments was applied by adding two-thirds of the normal weekly amount of irrigation water. The results achieved in the very dry Arizona climate, with its high vapor pressure deficit, may not be representative of plants in more humid areas that may not experience such severe stress even though the percentage drop in amount of water from well-watered to droughted may be much greater. Alternatively, plants that live through much more extended drying cycles may experience more severe stress than these mild and constant stresses.

Drought stress and metabolism. Carbon assimilation rates of drought-stressed plants grown under CO_2 concentration of 650 μL/L exceeded that of plants in current atmospheres of CO_2 by 39% (Kimball et al., 1984) or 52% (Radin et al., 1987). But photosynthesis in plants deprived of adequate water showed a saturation response to c_i, unlike well-watered plants that kept increasing assimilation with c_i up to 700 μL/L (Radin et al., 1987). Again, even the substantial rise in photosynthesis does not account for yield increases seen with high levels of CO_2. Kimball et al. (1986) found no effect of drought stress alone on photosynthesis, though well-watered plants showed a greater positive effect (70% increase) of CO_2 enrichment on photosynthesis (Radin et al., 1987).

While Kimball et al. (1986) found that drought stress caused leaf temperatures to rise, they observed no concomitant, significant drop in stomatal conductance with drought stress. As noted above, according to new calculations of Idso and Allen (1988) this could be an artifact of steady-state porometer methodology. However, Radin et al. (1987) saw increased stomatal closure in drought-stressed plants responding to elevated amounts of CO_2.

CHAPTER 6

CORN

Corn or maize (Zea mays L.) is a very high-yielding C4 grass of Central American origin that has been bred by humans for grain production for 25,000 years. Maize is the third largest crop in the world, with production highest in North America and acreage highest in Asia (Coulman, 1987; Roecklein and Leung, 1987; Starling, 1987). It is the number one U.S. crop, whether counted by acreage with 20.9 million ha in 1983-84, or by production with 106.8 million metric tons in the same years (Coulman, 1987; Roecklein and Leung, 1987; Starling, 1987). In this country corn is used extensively for animal feed and for processed foods, often as corn flakes, high-fructose corn syrup, corn oil, and corn starch. In other countries, maize is still a primary part of the human diet, as flour for tortillas and bread or as a vegetable. It has many industrial uses, including alcohol, adhesives, paper, linoleum, paint, soap, and textile sizing (Roecklein and Leung, 1987; Starling, 1987).

PHOTOSYNTHESIS

Despite its economic importance to American agriculture, very little research has been done recently concerning the effects of elevated carbon dioxide concentration on this crop. The lack of study on corn probably stems in part from the fact that plants like corn which use the C4 pathway of photosynthesis already trap ambient CO_2 quite efficiently. Therefore, corn showed no photosynthetic increase (in CO_2 fixation) with increases in carbon dioxide concentration (Rogers et al. 1983a,b; Surano and Shinn, 1984). However, Usuda (1987) recently found that increasing internal CO_2 level of maize increased the concentrations of intermediates of the pentose phosphate pathway, which in turn increased the level of total C4 cycle intermediates, indicating a possible effect on photosynthetic carbon metabolism.

YIELD

Although few effects on photosynthesis have been noted, biomass of these plants does increase with moderate increases in carbon dioxide concentration. At 600 ppm CO_2, total plant weight increased 24% (Carlson and Bazzaz, 1980) or 7% across several water treatments (King and Greer, 1986); at 850 ppm King and Greer (1986) found no further increase, but at 910 ppm Rogers et al. (1983b) observed a 60% rise in dry matter over ambient concentration of carbon dioxide. At 1200 ppm CO_2, Carlson and Bazzaz (1980) found a 7% decline in biomass production.

Rogers' research group (1983a,b) also found enhanced growth of plant parts, including leaf area and seed yield. They suggested that the increases in leaf area and biomass occurred because the plants grown in high partial pressures of CO_2 did not wilt on hot summer afternoons. The wilting observed at ambient levels of CO_2 inhibits leaf expansion. Surano and Shinn (1984) found that carbon dioxide enrichment increased root growth in well-watered plants and stem height in drought-stressed plants, but had no effect on yield in either case. In contrast to effects seen in species using the C3 pathway of photosynthesis, high carbon dioxide concentration had no effect on leaf thickness, node number, number of reproductive parts (Rogers et al. 1983b), or partitioning of dry matter (King and Greer, 1986).

PHENOLOGY

Leaf emergence occurred more rapidly in corn plants subjected to 850 μL/L carbon dioxide than in plants grown in 350 μL/L. The former also consistently had significantly ($P = 0.001$) more fully senesced, nongreen leaves than the latter, indicating an acceleration of phenology in the plants exposed to high partial pressures of carbon dioxide (King and Greer, 1986). But Surano and Shinn (1984) found no effect on phenology of corn in CO_2 enrichment.

STOMATAL RESPONSE, TRANSPIRATION, AND WATER-USE EFFICIENCY

Stomatal conductance in corn decreased from 1.8 to 0.8 cm/sec as carbon dioxide concentration rose from 340 ppm to 910 ppm (Rogers et al. 1983a,b). Morison and Gifford (1983) found the stomatal responses of corn and of Paspalum plicatum, another C4 grass, were similar to that of rice and another C3 grass. All four species showed greater stomatal sensitivity when stomatal conductance was largest, that is when carbon dioxide concentration was low and VPD was high.

Transpiration was reduced whether maize plants were grown for 35 days in a glasshouse (Carlson and Bazzaz 1980), in controlled environments, (Morison and Gifford, 1983; King and Greer, 1986), or for 3 months in open-top field chambers (Rogers et al. 1983a,b). Water-use efficiency improved in all cases, up to 55% in the controlled environment (King and Greer, 1986).

LEAF TEMPERATURE

Corn leaf temperature, like that of all other species measured, rose in response to carbon dioxide enrichment (Morison and Gifford, 1983, 1984). This is not surprising, since the drop in stomatal conductance in corn exposed to high CO_2 concentrations was the largest of any crop in the literature. Corn is very tolerant of high temperatures; like all C4 plants it is not subject to high temperature-induced yield losses due to photorespiration. But combined with rising temperatures predicted by climate change, corn leaf temperatures may increase enough to actually inhibit some phases of plant metabolism (Hesketh and Hofstra, 1975).

DROUGHT STRESS

Surano and Shinn (1984) observed no effect of high concentrations of carbon dioxide on yield, biomass, leaf area, or number and weight of ears in corn plants that were deprived of adequate water, which was similar to the findings of Gifford and Morison (1985) on Paspalum plicatum, another C4 grass. In contrast, King and Greer (1986) observed that droughted corn had a greater percentage response to CO_2 enrichment of total plant dry weight and of grain yield than did control plants (as long as there was enough water to produce grain at all). However, additional amounts of carbon dioxide did not make up for the very large yield reductions caused by drought (King and Greer, 1986).

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POTENTIAL EFFECTS OF CLIMATE CHANGE ON PLANT-PEST INTERACTIONS

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FINDINGS[1]

The literature survey indicated that temperature increases associated with the climate change scenarios could result in the following trends: (1) Overwintering survival will increase for migratory and nonmigratory insect pest species. (2) Northern range will extend for current pests in the higher latitudes and result in southern species migrating into upper Grain Belt regions. (3) Pest species with multigeneration per year life cycles will increase in upper Grain Belt areas. (4) Pest populations will establish earlier in the growing season, which would result in pest populations being particularly abundant during the more susceptible growth stages of crops.

The results of modeling earworm (Heliothis zea)-soybean interaction showed that this pest, under warming climate conditions, will increase dramatically in severity in Grain Belt areas. It is predicted that the extent of damage by this species will result in significant economic losses by grain farmers in the Midwest. This result was particularly marked with the GFDL scenario. Both GFDL and GISS models predicted northward range extensions in overwintering capability for four insect pest species: potato leafhopper, black cutworm, sunflower moth, and green cloverworm. This pattern indicates that there is the potential for at least these pests to move northward and invade cropping systems earlier in the growing season.

Regression analysis incorporating both temperature and precipitation variables indicated significant cropping system-pest interactions. In general, corn acreage decreases with increasing temperature scenarios. This change will be greater in southern and western areas than in the more eastern areas of the Grain Belt. Insect severity increased with temperature rise in the Lake State region and decreased in severity in the southern region of the Grain or Corn Belt. Insect pest severity on soybean increased with temperature rise in all regions. The literature survey and modeling suggest that the result of climatic warming could result in a substantial rise in pesticide use with the accompanying environmental hazards. This report recommends increased emphasis on integrated pest management targeted toward the predicted climate changes.

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CHAPTER 1

APPROACH AND OBJECTIVES

Compared to the existing information on the potential climate change effects on crop physiology and agronomic production parameters, there has been relatively little effort directed toward assessing the influence of climate change on plant-pest interactions. Atmospheric increases in temperature and CO_2, and changes in moisture regimes, all have the potential to affect interactions between pest organisms and crops either directly or indirectly.

In this report, we will identify insect pest interactions of major agronomic significance that are sensitive to climate change. Major emphasis is placed on temperature increase effects, particularly in relation to the Great Lakes and Midwestern Grain Belt regions.

The objectives of the report are as follows:

1. Formulate key ecological concepts and compile a literature survey relating projected temperature change scenarios to the major classes of mechanisms by which pest-crop interactions could be influenced.
2. Model the effects of climate change scenarios on a major insect pest-crop relationship.
3. Suggest needs for future research and policy development.

In preparing this report, we have had to make a number of assumptions that we feel are somewhat unrealistic, though necessary for a first attempt in formulating a response to the risk of undesirable change to the agroecosystems due to climate change. While we consider it highly probable that there will be major changes to the agricultural system as we know it over the next decade and beyond, we have been forced to make the assumption that there will be no fundamental changes to the way agriculture is conducted, except as a function of climate change. Thus we have based our analyses on agricultural practices as they currently exist, although the authors are cognizant of projections for agricultural practices to change in the future. In particular, there is considerable interest in a growing movement toward the adoption of lower chemical and energy inputs to farming systems in order to sustain and stabilize productivity and to minimize negative environmental inputs. Cropping system design is expected to change accordingly. Should this trend become a major trajectory for agricultural change, we believe that the analyses and conclusions concerning climate effects on insect populations will remain valid. However, the impact of the climate/insect interactions on agricultural productivity and economics would vary with specific agricultural practices and the nature of future cropping systems.

We have strictly limited our discussion to basic biological processes that we know to be temperature driven, and attempted to construct likely scenarios of population changes in response to increased heat availability. Our end point is an assessment of what this may mean to agricultural production and costs. Essentially we have taken a population biology approach and measured the outcome on crop damage resulting from shifts in spatial and temporal distribution combined with changed, usually increased, longevity and fecundity of pest insects. We have interpreted crop damage in terms of costs in control measures as well as yield reduction: both these factors are central issues for the farmer attempting to make a living from the land.

Because of our own expertise, we have limited our discussion to two crops: corn and soybeans. They are, in the Midwest, the two most important crops, and so constitute a major agricultural investment. We foresee that there may be shifts in the economics of these crops due to both macro-economic trends and to climate warming. We have made the assumption that these crops will remain important for the next two or three decades. Our arguments, however, apply to other crops that we have not considered: rangeland, forests, cotton, as well as small grains and vegetables will be influenced by shifts in pest status. For some of these crops, management and predictive models exist that might be used to investigate in more detail possible changes to the distribution and economics of these commodities.

Throughout this report we have assumed we know which pests will be dominant. This is probably the least supportable assumption. We know so little about the millions of insects in the world that it is virtually impossible to predict which ones will be pests: there are innumerable instances of closely related species living in the same crop, only one of which is ever a serious pest. We know far less about the nonpest species, so that the impact of climate change on pest status is impossible to estimate. We believe that it is entirely possible that a warming trend could reduce the pest status of one species, only to increase the status of a relative. To be able to guess which potential pests will actually become pests under certain circumstances requires long-term monitoring of pest and nonpest species' populations. This essential work has never been done in North America.

In spite of these caveats, we unhesitatingly predict that there will be changes to insect-plant relationships, and we outline what kind of changes are possible, and furthermore we predict that these plant-pest interactions will contribute to changes in the economics of agriculture.

CHAPTER 2

ECOLOGICAL MECHANISMS AND LITERATURE REVIEW

Within this section, we develop concepts and review the literature on some of the major mechanisms through which climate change may impact upon pest-plant interactions. Table 1 summarizes the major crop pests by region for the reader's convenience.

ABIOTIC STRESS

Adverse abiotic conditions can stress both arthropods (Scriber and Slansky, 1981) and plants (Boyer, 1982). "Stressed" indicates that arthropod or plant physiology has been deflected away from optimum by an external factor (e.g., heat, moisture), and such stress results in reduced survival, growth, or reproduction (Odum et al., 1979). Drought stress will likely increase in frequency in the midwestern and southern United States as the climate of these regions becomes warmer and drier. Drought is often associated with pest outbreaks (McPherson and Allen, 1981; Wallner, 1987). Drought, however, can both directly impede the growth of some pest populations by creating suboptimal conditions for reproduction and survival (e.g., Stinner et al., 1982), and indirectly benefit population growth of others by altering plant characteristics (e.g., food quality) (Mattson and Haack, 1987a,b). Also, the effects of drought on plants and pest populations interact in complex ways with xenobiotics including air pollutants, for example, ozone (Heagle et al., 1987; Flagler et al., 1987; King and Nelson, 1987; King, 1987) and sulfur dioxide (Black, 1982; Hughes et al., 1982; Hughes et al., 1983; Griffith and Campbell, 1987), as well as pesticides (Wrensch, 1985; Kogan and Turnipseed, 1987). Despite these complexities, most current evidence indicates that pest populations will be enhanced by warmer, drier conditions, particularly in the northern portions of their ranges and in spring when cool temperatures and rainfall limit population growth.

Direct effects of stressful climate conditions on arthropod reproduction, survival, and movement are documented for many species. Reproduction, fecundity, and hatching success of foliage-dwelling arthropods can be markedly reduced by temperature and humidity that are too high or low (e.g., Sprenkel and Rabb, 1981; Moscardi et al., 1981b). Fecundity and larval survival of Mexican bean beetles (Epilachna varivestis), a pest of soybeans and many other leguminous crops, can be severely reduced by moderately high temperatures and low humidity (Kitayama et al., 1979; Lockwood et al., 1979; Sprenkel and Rabb, 1981; Wilson et al., 1982; Mellors and Bassow, 1983). However, fecundity of spider mites (Tetranychus spp.), pests of many crops including soybeans, apples, maize, sorghum, wheat, and tomatoes, is favored by warmer temperatures and reduced at high humidity (Wrensch, 1979, 1985). Indeed, during the summer of 1988 when the entire U.S. Corn Belt experienced its worst drought in the past 100 years along with higher than normal temperatures, twospotted spider mites (Tetranychus urticae) became a severe problem on soybeans throughout the whole region. In Ohio alone, acreage sprayed was estimated to be over 1 million acres, with cost-to-control and loss estimates in that single state placed at $15-20 million (unpublished data). In other Corn Belt states where soybean acreage is much higher, estimates of acreage sprayed and losses were even greater. Estimates indicate that up to 8 million acres were sprayed with insecticides for spider mite control.

Parasitoids released to control pests have highest emergence rates within relatively narrow ranges of humidity and temperature (e.g., Powell et al., 1981; Orr et al., 1985). For pest species with soil-dwelling stages, suboptimal soil moisture (e.g., Regniere et al., 1981) and temperature (e.g., Marrone and Stinner, 1983) can significantly reduce egg and/or larval survivorship in the soil. Marrone and Stinner (1983, 1984) found that survival of bean leaf beetle (Cerotoma trifurcata) eggs was greatest at intermediate levels of soil moisture and temperature, and that survival of larvae and pupae was lower in dry soils. Survivorship of larval and adult pests and predators will likely be enhanced by the predicted climate changes. Survivorship of pests can be dramatically lowered by ephemeral, adverse weather events such as heavy rainfall (Jones, 1979; Puttaswamy and Channabasavana, 1981; Wellington and Trimble, 1984), but summer populations may reach high numbers when

Table 1. Major Insect Pests and Pathogens by Region for Corn and Soybeans

REGION	INSECTS	PATHOGENS
CORN		
Northern Plains	Corn rootworms, European corn borer, cutworms, mites, grasshoppers	Stalk rots, charcoal rot, ear rots, goss' leaf blight, seed rots
Lake States	Corn rootworms, European corn borer, armyworm, cutworms, stalk borers	Stalk rots, eyespot, ear rots, smut, northern leaf spot
Corn Belt	Corn rootworms, European corn borer, cutworms, stalk borers, wireworms	Stalk rots, northern corn leaf blight, ear rots, southern corn leaf blight, nematodes
Delta States	European corn borer, cutworms, armyworm, fall armyworm, white grubs	Charcoal rot, stalk rots, ear rots, viruses, helminthosporium
Southeastern States	Billbugs, European corn borer, cutworms, wireworms, southern corn rootworm	Aspergillus, nematodes, stalk rots, viruses, seed rots
SOYBEANS		
Northern Plains	Green cloverworm, Mexican bean beetle, bean leaf beetle, corn earworms, cutworms	Phytopthora, seed rots, charcoal rot, pod and stem blight, stem canker
Lake States	Green cloverworm, cutworms, spider mites, potato leaf hopper, bean leaf beetle	Phytopthora, seed rots, brown stem, pod and stem blight, brown spot
Corn Belt	Mexican bean beetle, bean leaf beetle, Japanese beetle, seed corn maggot, corn earworm	Phytopthora, cyst nematodes, pod and stem blight, brown stem, brown spot
Delta States	Corn earworm, soybean loopers, stinkbugs, velvetbean caterpillar, green cloverworm	Anthracnose, cyst nematodes, pod and stem blight, charcoal rot, seed rots
Southeastern States	Corn earworm, stinkbugs, soybean loopers, velvetbean caterpillar, bean leaf beetle	Cyst nematodes, root knot nematodes, stem canker, brown spot, and stem blight

REGIONS:
Northern Plains = Colorado, Kansas, Nebraska, N. Dakota, S. Dakota
Lake States = Michigan, Minnesota, Wisconsin
Corn Belt = Illinois, Indiana, Iowa, Missouri, Ohio
Delta States = Arkansas, Louisiana, Kentucky, Mississippi, Tennessee, Oklahoma, Texas
Southeastern States = Alabama, Georgia, N. Carolina, S. Carolina

conditions are drier and populations are not checked by such intermittent events. Survivorship of predators may also be enhanced by moderately drier conditions as, for example, survivorship of juvenile spiders is reduced by heavy rainfall (LeSar and Unzicker, 1978).

Climate conditions may differentially affect the survivorship of males and females skewing sex ratios (Walker, 1984), and hence potentially influencing population growth rates (see below). Movement of arthropods, both local (e.g., Blau and Stinner, 1983) and migratory (Rankin and Rankin, 1979), will likely be increased by the predicted climate changes. Temperature, humidity, and wind seem particularly important in determining the proportion of arthropods moving (Wolfenbarger, 1975) and the spatial extent of their movements (see Rabb and Kennedy, 1979; Pedgley, 1982; MacKenzie et al., 1984). Warmer temperatures are often associated with greater movement. For example, Ives (1981) found that local movement rates of coccinellids (a major predator of aphids) significantly increased with temperature. Also, increased rates of movement of many species are often associated with stressful environmental conditions. Kennedy and Smitley (1985) report that movement of spider mites is stimulated by declining host plant quality, high population density, and particularly, low relative humidity. Aerial transport of pathogens is also strongly affected by temperature, humidity, and wind (Pedigo et al., 1983; Davis, 1987). The indirect effects of abiotic stress on pest arthropods through changes in host plant quality may have greater impact than the direct effects described above. Host plant quality is determined by the balance between numerous morphological and biochemical factors including the host plants' content of nutrients (particularly nitrogen-containing compounds) and defensive compounds (Rhoades, 1979; Strong et al., 1984; Brodbeck and Strong, 1987), and is an important factor affecting pest populations because it is a major determinant of arthropod reproduction (Wermelinger et al., 1985; Wellings and Dixon, 1987), survival (e.g., Rufener et al., 1986), and movement (Rankin and Singer, 1984). Host plant quality for herbivores is often enhanced by drought-induced plant stress (White, 1984; Mattson and Haack, 1987a,b), but may be lowered when plants are stressed by conditions including foliar damage (Carroll and Hoffman, 1980; Reynolds and Smith, 1985; Kraemer et al., 1987), soil nutrient deficiency (Muller et al., 1987), and numerous other environmental factors (see Kogan and Paxton, 1983).

Reduced host plant quality due to plant stress has been been associated with increased concentrations of plant defensive compounds (Gershenzon, 1984), but can be caused by changes in foliar nutrient or water content (Scriber and Slansky, 1981), or increases in the C/N (carbon/nitrogen) ratio of foliage (see Lincoln et al., 1984). As atmospheric concentrations of CO_2 rise, C/N ratio will increase, and higher C/N ratio of foliage will stimulate greater feeding by some herbivores (Lincoln et al., 1984). Major crop types will be differentially affected by such increased herbivory because C/N ratio will increase more for plants with C_3 metabolism (e.g., soybeans, wheat, rice) than for C_4 plants (e.g., corn, sorghum, sugarcane) (Kimball, 1983). Because both increases in host plant quality due to plant stress and rising C/N ratio will stimulate feeding by pests, greater crop damage is likely for most climate change scenarios.

INTERSPECIFIC INTERACTIONS

Interspecific interactions among pests, pathogens, parasites, and predators are of major importance in agroecosystems because there is strong evidence that natural enemies, in many cases, significantly reduce pest populations (Price, 1987). Interspecific interactions in agroecosystems can be highly complex (Duffey and Bloem, 1986), and although agroecosystems often have low species richness (Odum, 1984), they usually possess all major structural components and types of species interactions found in natural systems (Risser, 1986). Current understanding of both natural and agricultural ecosystems indicates that a minimum of three trophic levels -- plant, pest, natural enemy -- interact to determine the dynamics of pest populations (Lawton and McNeill, 1979; Price et al., 1980; Duffey and Bloem, 1986).

Furthermore, a strong argument can be made that interspecific interactions are best viewed as part of the functioning of whole agroecosystems (House and Stinner, 1983; Wiens, 1984; Tilman, 1986; O'Neill et al., 1986). For example, spatial variability in soil moisture, nutrient availability, or plant competition can affect host plant quality for herbivorous arthropods (Harborne, 1982; Coley et al., 1985, and see above). Herbivores tend to aggregate in patches with higher host plant quality (Hassell and Southwood, 1978; Stiling et al., 1982), and natural enemies (predators, parasites and pathogens) cause greatest mortality where prey are concentrated

(Hassell and Southwood, 1978; Yeargan et al., 1983; Reichert and Lockley, 1984; Ewald, 1987). The linkage between all trophic levels, from soil nutrients to parasitoids, is clear and permits a broad range of complex dynamics throughout agroecosystem food webs.

Climate changes may have strong effects on interspecific interactions within agroecosystems. Pest-parasite and pest-predator interactions should be particularly sensitive to such changes because temperature often differentially affects interacting species (Hughes et al., 1984; Strong et al., 1984; Mattson and Haack, 1987a), potentially "releasing" pests from control by natural enemies (Risch, 1987). For example, aphid populations (aphids are pests of major crops including corn, cotton, alfalfa, peas, hops, and potatoes) are able to maintain positive growth at lower temperatures than their parasites and predators and may escape control by natural enemies during periods of cool weather (Wellings and Dixon, 1987). However, warm temperatures enhance the activity of predators and parasites (e.g., searching rates, attack rates, and handling times) and make them capable of causing the local extinction of aphid populations (Van Emden, 1966). Although local extinction of a pest species may seem beneficial for crop production (see Murdoch et al., 1985), such a phenomenon may also result in the decimation or extinction of natural enemies due to starvation, thus increasing the probability of pest outbreaks at a later time (Ferro, 1987). Pests usually have greater dispersal abilities than their natural enemies (Price, 1976; Mayse and Price, 1978; Rey and McCoy, 1979). The models of May (1986) suggest that pest-pathogen dynamics are most stable when both pest and pathogen are maintained together in the environment at low abundances, and Hassell (1981) reports that biological control of pests is more successful in perennial than annual cropping systems, probably because perennial crops permit a continuous interaction between predator and prey.

A second major way in which climate changes may affect interspecific interactions involving pests and natural enemies within agroecosystems is through effects on crop plants. Greater crop growth associated with CO_2 increase (Rodgers et al., 1983) probably will not affect pest populations because few species are currently limited by the amount of food available (White, 1984); however, increases in food quality due to plant stress (see above, Abiotic Stress) may permit dramatic increases in the growth rate of pest populations (White, 1984; Brodbeck and Strong, 1987), obviating control by natural enemies that have greatest impact on slow-growing pest populations (Schultz, 1983; Duffey and Bloem, 1987). Sap-feeding arthropods (e.g., planthoppers that are major pests of rice) seem most strongly favored by stress-induced changes in host plant quality (McNeill and Prestige, 1982; Buckley, 1987). Decreases in host plant quality that slow the growth of pest populations may enhance the effectiveness of natural enemies in controlling pest populations (Schultz, 1983; Duffey and Bloem, 1986).

A third mechanism in which climate change may alter interspecific interactions involving pests is by alteration of the structure of pest-natural enemy communities within agroecosystems (Liss et al., 1986). Geographical range extensions and phenological shifts in species occurrences and relative abundances will create new interactions between species and probably alter the dynamics of existing interactions. These changes may be particularly dramatic where generalist predators and parasites (i.e., those that prey on numerous insect species) predominate, such as in soybean agroecosystems (Turnipseed and Kogan, 1983). Switching of a generalist predator between prey types may stabilize simple predator-prey systems (Luck, 1984), but in more species-rich systems, generalist predators or parasites may compete for prey (Liss et al., 1986), and "apparent" competition (Holt, 1977) may occur between prey species. Also, beneficial predators and parasites may victimize each other, potentially reducing their abilities to control pests (Messenger, 1975). Evidence that shifts in community interactions may destabilize existing communities and result in outbreaks of pests comes from studies of (1) species introductions (e.g., Messenger, 1975), and (2) disruption of food webs by insecticides (see Metcalf, 1986; Ferro, 1987), and modeling studies of species removals (Redfearn and Pimm, 1987). Whether the climate changes associated with a doubling of CO_2 will stabilize or destabilize interspecific interactions involving arthropod pests will depend on the following: (1) the type of crop and stage of development; (2) the type, magnitude and duration of plant stress; (3) the types and developmental stages of the pests and natural enemies involved; and (4) the differential impact of climate change on pests and natural enemies. We currently lack much of the ecological information needed to make predictions about the outcomes of such complex interactions for even the best known cropping systems. However, the differential effects of weather on pests and natural enemies (see above), and the association of pest outbreaks in agroecosystems with periods of warm, dry weather (Risch, 1987), strongly suggest to us that destabilization of arthropod communities and a consequent increase in the frequency of pest outbreaks is likely.

POPULATION GROWTH RATES

Whether a potential pest causes economic damage in a particular year is often determined by the favorableness of the environment for population growth. Conditions of climate, food quantity and quality, and the abundance and activity of natural enemies determine environmental favorableness. Climate is, perhaps, the most important factor because it also strongly affects food quality (see Abiotic Stress), the functional and numerical response of parasites and predators (Hassell and Southwood, 1978), and the virulence and spread of pathogens (e.g., Pedigo et al., 1983; Boucias et al., 1984). Climate directly influences six variables that significantly affect the growth of pest populations: (1) initial population size (i.e., the number of overwintering survivors); (2) developmental rate (and hence time to reproductive maturity); (3) per capita lifetime fecundity; (4) survivorship of immature and adult stages; (5) sex ratio of the population (particularly for species with parthenogenic capability); and (6) movement (i.e., dispersal) rates. Effects of climate change on overwintering survival, fecundity, survivorship, and movement are each dealt with in other sections of this section; hence, only developmental rate and sex ratio are elaborated here. The rate of arthropod physiological development (developmental rate) can strongly influence the growth of pest arthropod populations (Snell, 1978; Hughes et al., 1984) and is largely determined by temperature, humidity, and food quality and quantity (Gordon, 1984). Developmental rate is maximized at optimal values of temperature and humidity (e.g., Wrensch, 1985), and distinct arthropod biotypes (populations adapted to local environmental conditions) have often been identified (e.g., Buckley, 1987). Shifts in rainfall or temperature regimes, therefore, might result in increased or decreased developmental rates, depending on whether prevailing environmental conditions are below or above optimum. Spring temperatures, and those at the northern edge of a species range, probably are lower than optimum; thus, temperature increases would result in shorter development times and more rapid increase of pest populations. Also, the developmental rates of many pest species will be indirectly favored by warmer, drier conditions because of increases in food quality (see Abiotic Stress). Where the growth rates of arthropod populations are altered by climate changes, smaller arthropods, e.g., aphids and mites, will likely be more affected than larger ones. Although smaller arthropods are more sensitive to adverse climate conditions (e.g., desiccation, heavy rainfall) than larger arthropods, smaller species usually have greater reproductive potential (e.g., greater fecundity, shorter development times, more generations per year), and hence are better able to track climatic fluctuations (Ito, 1980). Population growth rates may also be enhanced by a shift in the sex ratio (M/F) toward more females (Hughes et al., 1984). Rapidly growing populations are characterized by a female-biased sex ratio (e.g., mites [Sabelis, 1985], aphids [Wellings and Dixon, 1987], pentatomids [Schumann and Todd, 1982]). Various external factors can influence sex ratio, including population density (Wrensch, 1985), food quality (Moscardi et al., 1981a), and differential mortality (Walker, 1984). The principal climate variable influencing sex ratio seems to be temperature. For example, Shepard and Gale (1977) found that higher temperatures favored the production of male Pediobius foveolatus (an important parasitoid of Mexican bean beetles), and hence would decrease population growth of this beneficial species. Sex ratio may be a particularly important variable driving the growth rates of populations containing all-female strains (Mitter and Schneider, 1987) or that are cyclically parthenogenetic (e.g., aphids and mites). Species with all-female strains occur in the orders Lepidoptera, Homoptera, and Coleoptera (Mitter and Schneider, 1987). The patterns in arthropod growth rates described above indicate that a warmer, drier climate will most enhance the population growth rates of small, sap-feeding arthropods with highly variable sex ratio or parthenogenic strains (e.g., mites and homopterans). Control of this group of pest species will be most difficult because pesticide resistance is prevalent and develops rapidly among these species (Metcalf, 1986). Population growth rates of all pest arthropod species will benefit from increases in temperature through its effect on development rates, particularly in spring and in the northern regions.

OVERWINTERING

Warmer temperatures will impact insect biology during those months in which crops are not growing or are dormant. The most critical time is during the cold months when pests endemic to a region must overwinter for survival. Higher winter temperatures have the potential to increase the survival rate of many pest species. Most insects falling into this group usually survive very well during the winter temperature extremes that occur, e.g., European corn borer and corn rootworms on corn, Mexican bean beetle and bean leaf beetle on soybeans.

However, extremes in low temperatures can play a significant role as a mortality factor that can serve to drastically reduce the following season's insect population. During the winter of 1983-84, a severe cold spell in the Midwest (two consecutive days of temperatures down to -24 C with little snow cover to act as insulation) was a partial reason given for the nearly total population reduction of both Mexican bean beetles and bean leaf beetles on soybeans (the other condition adding to their mortality was a drought during the summer of 1983). A similar decline in overwintering survival brought about by a short period of extreme cold winter temperatures was observed in Louisiana for bean leaf beetle in 1982 (Payah and Boethel, 1985). As average winter temperatures rise, the extreme low temperatures associated with overwintering mortality might not occur as readily, i.e., diurnal variability would remain relative to increased average temperatures. Thus, insects currently overwintering in the North that are affected by such extremes should successively overwinter more frequently, with higher survivorship.

Numerous pests of corn and soybeans, unable to overwinter in northern regions owing to cold winter temperatures, migrate from warmer climes prior to becoming economic problems. Black cutworms on corn in northern midwestern states (Von Kaster and Showers, 1982; Beck, 1987) and green cloverworm on soybeans in all the Midwest (Wolf et al., 1987) are two important examples of such crop pests. Although warmer average temperatures during the winter might allow these insects to overwinter farther north, it is still uncertain whether they will become greater problems in these newer overwintering areas. Green cloverworm, for example, is not a significant problem on soybeans where the insect currently overwinters. Examining the insect's damage potential in areas of their current overwintering is helpful in determining their future damage potential.

An additional consideration should be given to those insects that are currently not pests in the Midwest because they do not migrate (1) in sufficient numbers or (2) early enough to cause economic losses. As an example, corn earworm passes through numerous generations in more southern climes, with the second generation damaging corn and the third and fourth generations causing damage to soybeans in late summer (Pedigo et al., 1981). The corn earworm migrates to more northern locations in midsummer and causes serious damage to sweet corn and, less frequently, to field corn. Populations do not have sufficient time to develop on soybeans, and thus, are not considered a problem on soybeans in the Midwest. If the ability of the corn earworm to overwinter in northern regions becomes greater because of warmer winters, population levels in the North might develop that could cause greater damage to field corn and, later in the summer, to soybeans (see Modeling section).

In summary, warmer winter conditions will probably improve the overwintering ability of certain insects while allowing others, currently unable to overwinter in the Midwest, to overwinter farther north. Whether this will increase an insect's damage potential is unclear; however, insects currently affected by severe winters should be more often present and in sufficient numbers in the spring.

GEOGRAPHIC EXPANSION

Related to overwintering ability is the geographical expansion that might occur with many corn and soybean pests. For insects such as the black cutworm and green cloverworm (Wolf et al., 1987) that migrate from warmer climes, any ability to overwinter farther north will increase their chances to extend their range northward. However, both these insects already reach the more northern limits of crop production. An insect that does not reach the more northern crop limits, or does so in insufficient numbers to be of importance, is the corn earworm. As discussed earlier, if this insect were able to overwinter farther north, we would see greater populations in the Midwest, sufficient to accumulate numbers on field corn and then move over to soybeans.

Where geographical expansion by an insect is of greater importance is in the predicted movement of crop areas into Canada. The question is whether insect pests in the Midwest will move concomitantly with the crop into these more northern regions. Because many of the insects are able to overwinter and develop into damaging populations under current conditions found in the Midwest, it is likely that they will expand into the more northern regions along with the crop. Indeed, Kogan (1981) has suggested for soybean pests that most of the oligophagous species associated with the crop adapted rather quickly throughout much of the range of soybean cultivation. He argued that the insects' expansion of their range into the most northern areas was probably limited by climatic factors as much as the lack or presence of the crop, and is one possible reason why those northern soybean growing areas do not have major pest problems. Assuming that other environmental conditions change appreciably along with temperature changes in the areas into which crops expand (e.g., soil type and moisture [rootworms and bean leaf beetles] presence of overwintering sites [Mexican bean beetles: Bernhardt and Shepard, 1978]), the pests will probably move with the crop. Whether there will be a time lag between when a crop expands into an area and when the pest insect arrives is unclear. However, if we can assume that temperature changes will occur slowly, allowing for a gradual migration northward of the crop rather than an abrupt movement, there should be an expansion of both crop and pest into these more northern areas. (Of special interest regarding geographical expansion is the situation with the European corn borer, for which we find varying generations -- from multiple in the South, two in the Midwest, to one in the far North. This difference in voltinism, resulting from the effect of environmental conditions on diapause induction, is discussed in the section on seasonal length).

Finally, certain southern insect pests that do not occur in the Midwest may expand farther northward with the advent of warmer temperatures. Indeed, we expect this expansion to occur because many of these insects might gain the capability to exist in the Midwest through the ability to overwinter farther north or by increasing their migrating range. However, we must not automatically assume all southern species will expand northward. An example serves to illustrate this point. The velvetbean caterpillar, a pest of soybeans in southern states, is not able to overwinter in most gulf coast states; overwintering occurs in the United States only in southern Florida, with most of the migrants arriving from Central America (Newsom et al., 1980; Buschman et al., 1981). Because future predictions are that the southern states will not see an increase in higher temperatures to the extent of the northern states, we expect the ability of the velvetbean caterpillar to overwinter in other regions of the United States to remain unchanged. It is unlikely that this insect species will be able to overwinter in the southern United States as it still needs the tropical conditions of Central America. If predictions are validated and southern states do become warmer and more tropical, the velvetbean caterpillar might indeed gain the ability to overwinter throughout the southern United States. In this latter scenario, the insect could become a much greater problem in the South, and also begin migrating to more northern regions.

SEASON LENGTH

If it is assumed that the predicted increase in average temperature occurs over the entire year, rather than being limited to the summer season, there should be a lengthened growing season for both corn and soybeans. Whether this addition to the cropping season is measured in weeks or months, and whether the extension is at the beginning of the season in the spring or the end in the fall (or both), would be speculative. Of primary importance, prior to examining the effect of a lengthened season on insect pests, is whether or not the crops will be modified by breeding to exploit the longer season. Soybeans (and corn to a lesser amount) are strongly affected by day length, which will not change as temperatures rise. Crops will first need to be developed for the longer season that will be experienced, knowing that the day lengths will remain the same. This varietal development will in all likelihood occur.

The effect of a lengthened season on insects will be variable depending on the insect's biology. For those insects that have two or more generations per year, a lengthened season might allow for additional generations and, thus, potentially higher population buildups. On soybeans, both the Mexican bean beetle and bean leaf beetle can have multiple generations, partially depending on the season length. Both insects have two generations in the Midwest and have three generations farther south in the Carolinas. In Minnesota, the bean leaf beetle has only one generation (Loughran and Ragsdale, 1986). Obviously, given a longer season for population development, both insects might develop a third generation in the Midwest and a second in more northern regions. Knowing that higher daily temperatures will accompany an increased season length will enhance the possibility of additional generations; thus, the damage potential will increase as well.

A longer season length, however, will not automatically increase the potential for additional generations. Other contributing factors to an insect's voltinism have to be taken into consideration. The European corn borer has three ecotypes in North America: a northern population, which is univoltine in Minnesota and Quebec -- a bivoltine ecotype appeared in Quebec in 1976, but has remained at low levels (Boivin et al., 1986); a central population in the Midwest (Iowa, Nebraska, and Ohio), which is bivoltine; and a southern ecotype (Alabama, Georgia, and southern Missouri) with three to four generations per year (Showers et al., 1975). This pest species has been successful in North America partially because of its adaptive plasticity, which allows it to modify voltinism to suit local conditions, voltinism being controlled by the diapause response (Showers, 1981). Lee and Spence (1986) believe that variation in diapause increases the insect's fitness in uncertain environments and suggest that at the northwestern edge of its range, Alberta, Canada, univoltinism is its safest strategy because a second-generation population would be unlikely to mature before the onset of winter in most years. Voltinism in the European corn borer is under control of thermoperiod -- Beck (1982) suggested a thermoperiodic response threshold of 17.5 C -- and photoperiod. The current understanding is that there is a significant interaction between the two; Beck (1987) states that the photoperiodic determination of larval diapause is strongly influenced by superimposed thermoperiods. As temperatures in more northern areas warm, this interaction between thermoperiod and photoperiod will become complex. While the former will be affected, the latter will not. The question is, with a warmer thermoperiod but similar photoperiod, will induction of diapause in the European corn borer be delayed so as to permit larvae from the first generation to pupate, leading to a second generation. Assuming that this occurs, a lengthened season (combined with more rapid developmental rates) should allow for the completion of a second generation. The bivoltine ecotype might begin to occur in locations farther north where it currently does not exist and might also become the dominant ecotype in areas where both ecotypes currently are present (e.g., Quebec).

For univoltine insect species, or those insects where phenology of the insect and plant is a more important criterion for causing damage, a lengthened season will probably not be important. Rootworms, a univoltine species, will not be affected by an increased season unless the biology of the insect changes to increase the number of generations (an unlikely scenario). For numerous insects, damage is limited to feeding during certain growth stages of the crop. Black cutworm is a species whose damage potential is directly related to crop phenology; it is a problem on seedling corn. The species does not cause damage to corn during other plant growth periods. A lengthened season will not cause the insect to damage other plant parts. Of more importance with rootworms and the black cutworm are their phenological relationships with the crop, i.e., whether the insects are present during the time when the damage potential is greatest (see section on phenology).

PLANT-PEST SYNCHRONY

The importance of phenological synchrony in affecting the severity of pest damage to crops has been demonstrated for a number of major pest species and their host plants -- European corn borer on corn, potato leafhopper on alfalfa, black cutworm on corn, and green stink bug on soybean, to name several specific interactions. It is not atypical to observe rigid requirements placed upon insects by phenological development of their host plants. Insect development can be severely hampered if synchronization with the host plant lags even several weeks out of phase (Strong et al., 1984). The key aspects of synchrony impact upon crop damage center on either (1) pest development exceeding crop growth (larger growth stages of insects can consume more crop biomass per unit time), or (2) pests being abundant when a crop is particularly vulnerable. Both of these mechanisms can be impacted very markedly by temperature. Our working hypothesis is that, in general, a warming trend would favor more rapid insect development over crop growth. During spring months in the Grain Belt, several of the major insect pests could accumulate degree days more rapidly, leading to earlier establishment of pest populations while crops are at young, relatively susceptible growth stages. This pattern would result in a lessened ability of crops to outgrow pest damage.

Waldbauer and Kogan (1976) presented data that indicated that a 3°C temperature increase during April and May would cause bean leaf beetle (Cerotoma trifurcata) to developmental time to decrease from 90 to 60 days. This temperature change would result in soybeans being attacked at a growth stage when the plants are quite vulnerable. Moreover, this temperature shift and more rapid development by the bean beetle would cause second-generation populations to peak before soybean senescence and consequently lead to increased damage on maturing seed pods.

Growth stages of crops vary in their susceptibility to insect feeding. Moscardi et al. (1981) reported that feeding by the velvetbean caterpillar declined as soybean phenology progressed. Additionally, 6th instar larvae of this pest consumed almost five times as much plant biomass as did 5th instar individuals. Growth rates in this insect, as with many species, are very temperature dependent, so that when insect growth proceeds at a more rapid rate because of increased temperature regimes, larger herbivorous insects will not only be present early in the growing season but they will also consume more biomass from the earlier, more vulnerable growth stages of crop plants.

In another experiment, Margolies and Kennedy (1984) found that the population of the spider mites (Tetranychus urticae) increased at a significantly greater rate on crops, both corn and legumes, when the plants were in the early vegetative stages versus later growth stages. Warmer growing temperatures would cause spider mite populations, a major pest of corn and soybean in the Midwest, to develop more rapidly, coinciding with earlier growth stages of these crops. This shift would presumably result in more damage by this pest species. In fact, this phenomenon was illustrated during the severe twospotted spider mite problem in the summer of 1988 referred to earlier in this report. In previous drought situations, mites have increased and damaged midwestern field crops in late summer (late August through early September) usually after the grain has matured. During 1988 when the drought began early in the spring and continued throughout most of the summer, the mite population explosion was also much earlier (mid-late July), and the damage to soybeans occurred during the critical flowering, pod development, and pod fill growth stages. The damage that occurred during these stages resulted in yield losses much greater than had ever been experienced.

A caveat needs to be added here that warmer climatic scenarios should also have the effect of shifting crop planting dates to a time earlier in the season. This shift could result in crops developing earlier and in turn influence synchrony between pests and crop net effect of this planting date. Pest development shifting could either be positive or negative in terms of crop growth.

Moisture conditions and drought incidence can also significantly influence crop-pest synchrony and subsequent crop damage. Menezes et al. (1985) found that green stink bug (Nezara viridula) populations and their impact on soybean yields were appreciably influenced by precipitation patterns impacting upon insect-plant phenological synchronies. Similarly, spider mite populations are higher and damage more severe under drought conditions. This pattern results both from increased mortality on the mites and a lessened ability of the crops to outgrow arthropod damage under water stress conditions (Simpson and Connell, 1973).

SUMMARY OF TRENDS FOR CLIMATE CHANGE SCENARIOS INFLUENCING ECOLOGICAL MECHANISMS FOR CROP/PEST INTERACTIONS

Based on the preceding literature review and our knowledge of plant/pest interactions, it is predicted that the climate change scenarios will:

1. Increase drought stress, leading to more insect outbreaks.
2. Increase C/N ratios in crop biomass thus stimulating feeding by some pest species.
3. Change temperature scenarios such that they have different impacts on pest insects and their natural enemies - predator and parasites.
4. Three-level trophic interactions -- crop, pest, and natural enemies -- are key in predicting the impact of climate change on pest severity.
5. Create new interactions between pest and natural enemies as geographical range extensions and phenological shifts in species occur.
6. Favor developmental rates of many pest species under warmer climate scenarios.
7. Increase overwintering survival potential for both migratory and nonmigratory insect pest species.
8. Result in northward range extensions of current pests in the higher latitudes and result in southern species migrating into upper Grain Belt regions.
9. Increase the number of generations of pest species with multigeneration per year life cycles in upper Grain Belt areas.
10. Result in pest populations being particularly abundant during the more susceptible growth stages of crops if pest populations establish themselves earlier in the growing season.

SIMULATION STUDIES OF AN INSECT-PLANT INTERACTION

Expansion of population or overwintering range as a result of an increase in winter temperatures is likely to have profound effects on the population dynamics of many temperature-limited insect species. This will be especially true for many migrant species that rely on overwintering survival in milder regions for their future summer success in cooler northern areas.

The present and potential overwintering ranges of four migrant species, which are major northern pests, are represented in Figures 1-4. The potato leafhopper, Empoasca fabae, is a serious pest on a wide variety of crops, including alfalfa and soybeans. At present, the species overwinters only in a narrow band along the coast of the Gulf of Mexico (Figure 1). Increases in winter temperature predicted by both the GFDL and GISS models suggest a doubling or tripling of the overwintering range, respectively. Increases in winter population density of this size would increase the invasion populations in the northern states by similar factors. The invasions would also be earlier; both features are likely to lead to increased insect load and damage.

The green cloverworm, sunflower moth, and black cutworm have more extensive ranges (Figures 2-4), so the increase in overwintering range as a result of climate warming will not be proportionally as great, but even these small increases are likely to have an impact on the population dynamics of these species. These are but a few of the insect pests that would be likely candidates to increase their damage potential as a result of climate warming.

We know enough about the population dynamics of all four of these species to speculate concerning what might happen but, unfortunately, not enough to be able to investigate in detail the likely consequences of climate change. In this section we will describe and use an insect-plant simulation model to investigate the potential for climate-induced changes in agricultural practices and profits in soybeans. The model, called SICM (for Soybean Integrated Crop Management), was made available to us by researchers at North Carolina State University. In particular, we would like to thank Dr. Gail Wilkerson who sent us the FORTRAN code in a form suitable for these investigations.

SICM was developed to allow researchers to study the effects on yield or profit of desired changes in crop management or changes in the biological structure of the crop, or crop-pest interactions (Jones et al., 1986). It comprises several component submodels: the crop, soil and water, economics, and three pests (velvet bean caterpillar, southern green stink bug, and corn earworm). All three species are pests of soybeans in North Carolina, but only the corn earworm, Heliothis zea, will be considered here. It is a cosmopolitan species, highly polyphagous, and highly mobile. At present it is a serious and regular pest of soybeans only in the southern states, but it is an ideal model insect for our purposes because it is a marginal pest on soybeans throughout the Corn Belt. The purpose of this investigation is to determine if climate change could trigger a change in the damage distribution of this species and, if so, to estimate the costs of increased corn earworm numbers on soybeans in the Corn Belt.

The Simulation Model

A variation of SICM, called STRATEGY, allows the simulation of many conditions and weather years to evaluate various production changes. STRATEGY uses historical weather data and expected market information to develop strategies to manage future cropping seasons. The major differences between SICM and STRATEGY are the interactive interface to select inputs to the model, and the level of reporting by the model. SICM allows detailed interactive selection of inputs and interactive graphic reporting of results for users who may not be familiar with computers. It is intended ultimately to be a practical management tool. STRATEGY, on the other hand is intended specifically for research work. It is the latter version we used to

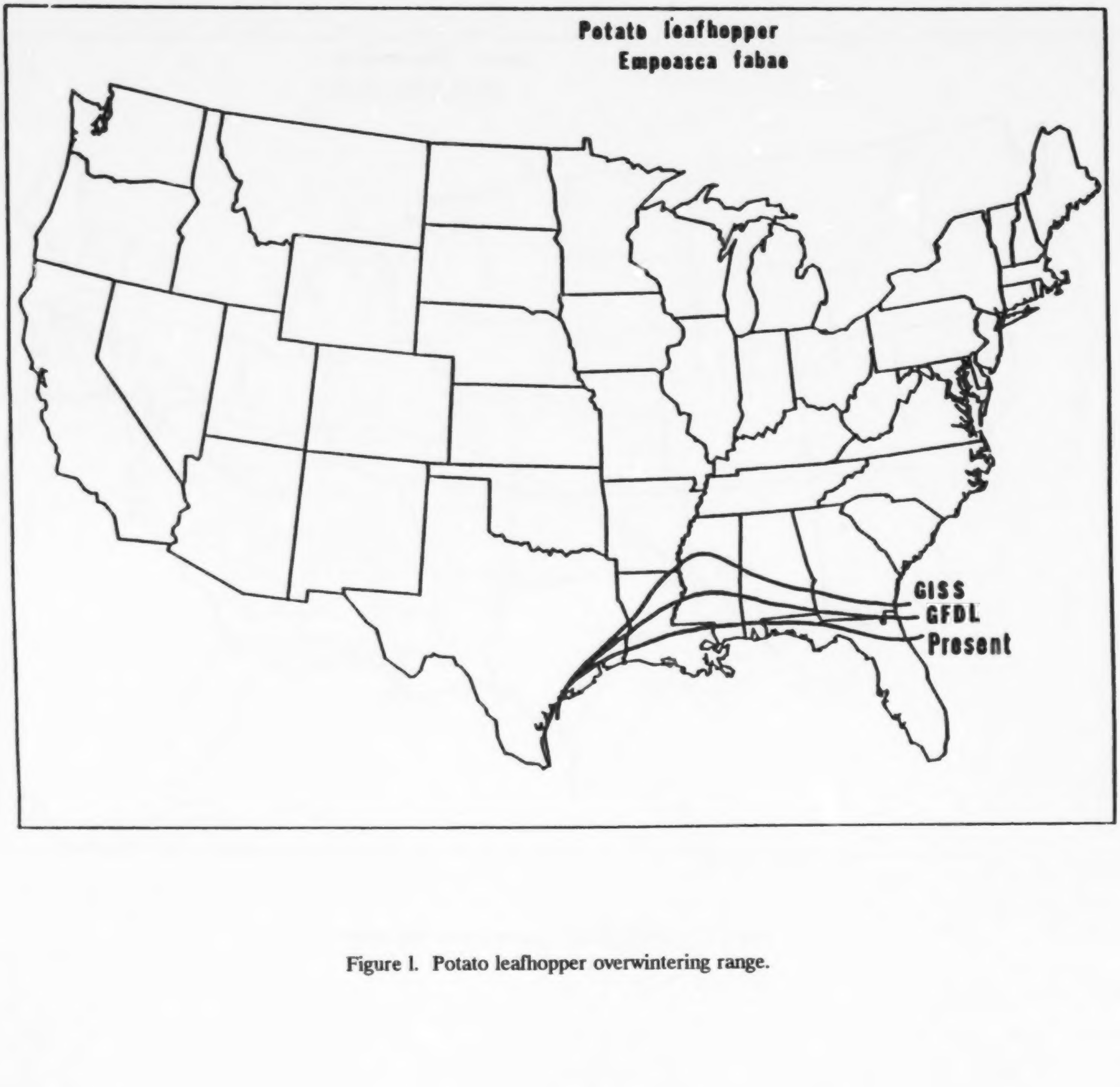
Potato leafhopper
Empoasca fabae
GISS
GFDL
Present

Figure 1. Potato leafhopper overwintering range.

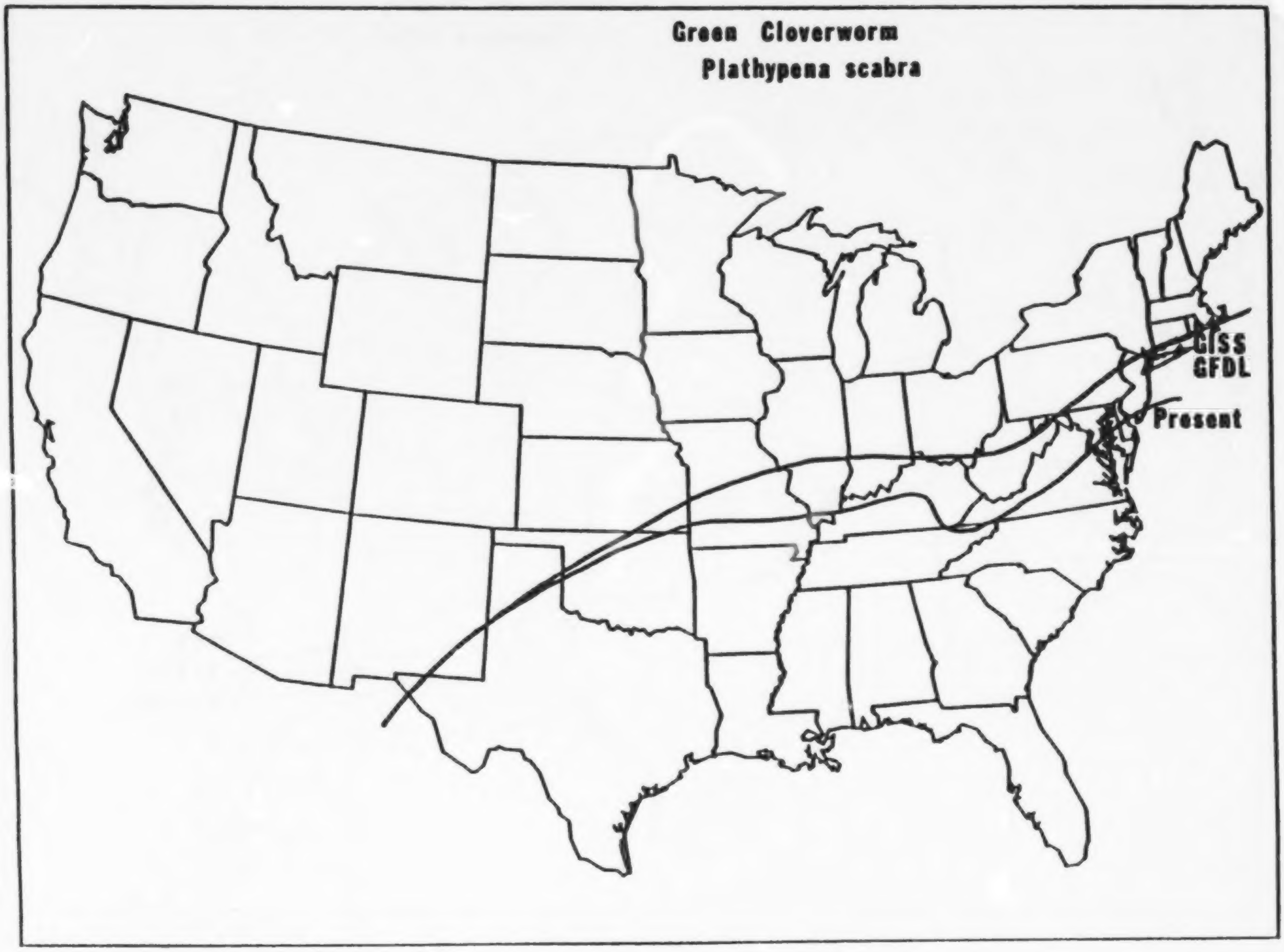
Green Cloverworm
Plathypena scabra
GISS
GFDL
Present

Figure 2. Green cloverworm overwintering range.

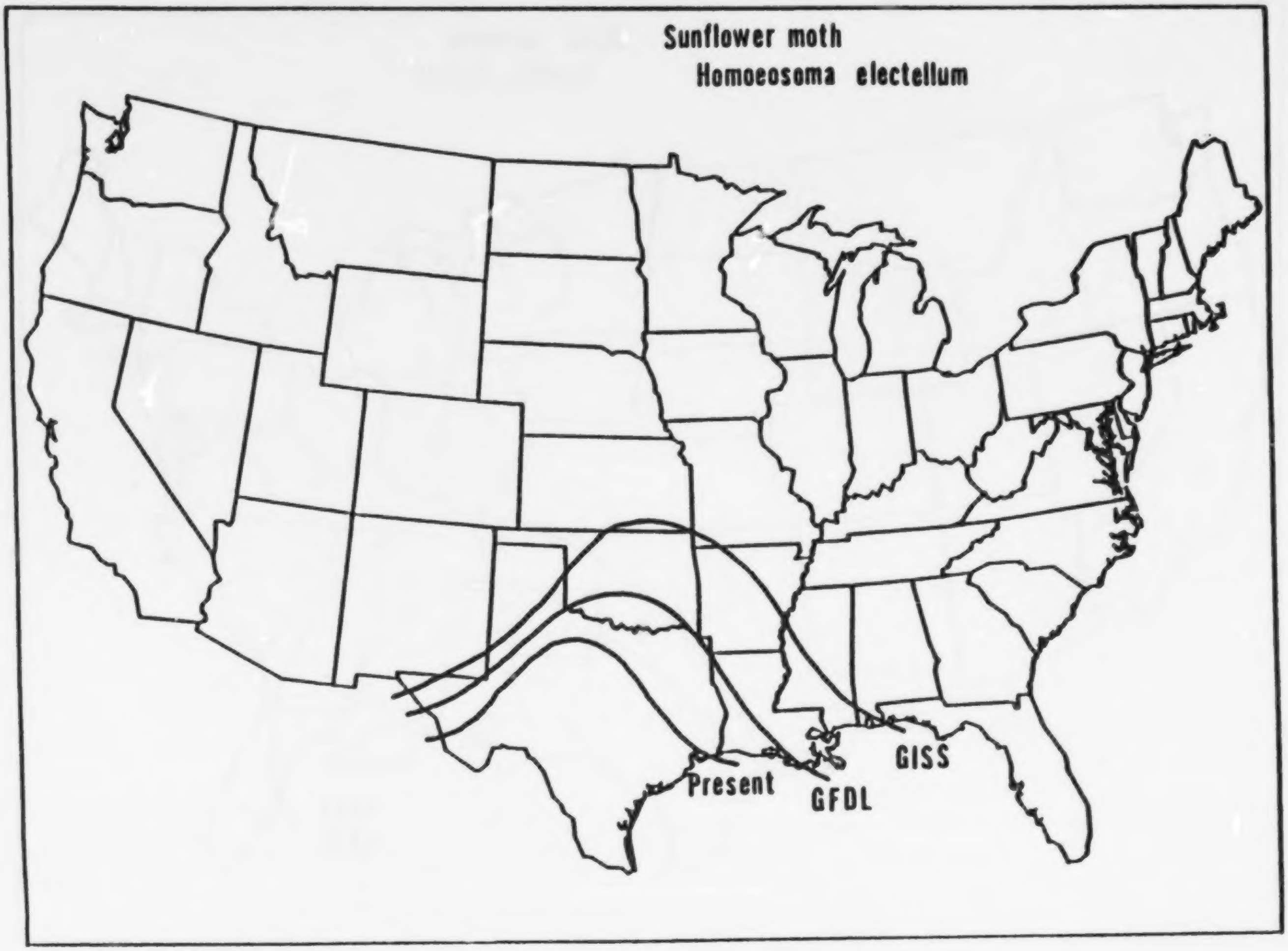
Sunflower moth
Homoeosoma electellum
Present
GFDL
GISS

Figure 3. Sunflower moth overwintering range.

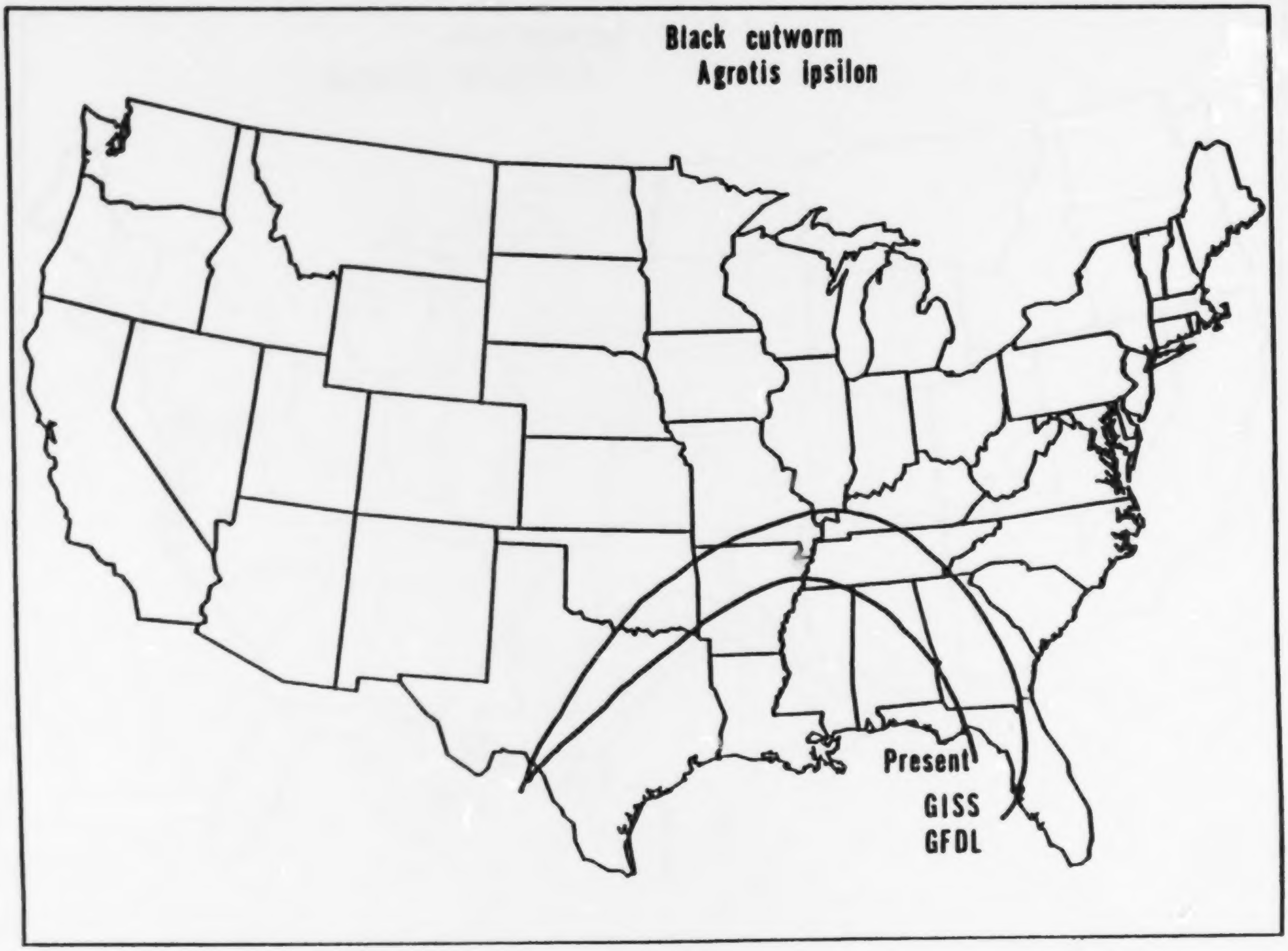
Black cutworm
Agrotis ipsilon
Present
GISS
GFDL

Figure 4. Black cutworm overwintering range.

investigate the potential consequences of atmospheric warming. What follows is a brief description of the plant and insect submodels extracted from the Jones et al. (1986) description of SICM. The economic and soil models are not described: soil and economic conditions were assumed to be constant.

Plant Submodel

For many crop plants, the partitioning of dry matter to growth in the different plant parts depends on the stage of development. In order to predict accurately the growth and yield of these crops, one must be able to predict the timing and duration of the various growth stages. Soybeans have several distinct stages of development between planting and final maturity. The stages of development for soybean, as described by Fehr et al. (1971) were used as a basis for the plant model, although additional stages are now defined. Six of the eleven stages depend on both night length (scotophase) and on temperature; others depend only on temperature. The reproductive stages of soybean depend on temperature and scotophase: soybeans flower sooner in long nights than in short ones. Some cultivars are highly sensitive to night length, whereas others are not. Soybean sensitivity to night length is the major source of soybean adaptation to various latitudes. A phenological model was developed to permit the prediction of timing and duration of stages under a range of latitudes and planting dates (Mishoe et al., 1985). For the temperature-sensitive phases, a physiological time approach was adopted. This approach is equivalent to degree-days for the range of suitable temperatures, but is more flexible in that it allows for decreased rates of development at higher temperatures. Plant transpiration is based on root length and soil water distribution and on the potential evapotranspiration rate, determined by weather conditions. The potential evapotranspiration rate is calculated from temperature and radiation. The actual plant transpiration, and thus the actual water extraction by roots, is the lessor of the potential rate and the water supplying capability of the soil-root system. The soil-root system capability is calculated from the rate of root water absorption per unit length of root (using the steady-state solution of the radial flow equation) multiplied by root length density. Since soil hydraulic conductivity varies with water content, water absorption may be limited by root length or by water content. Water stress occurs when the water supply to the root system is less than demand. Photosynthesis is reduced in proportion to the ratio of supply to demand. Leaf and stem growth rates are reduced when the supply to roots is less than 1.5 times the potential evapotranspiration rate. Thus as soil dries or as roots are damaged, water stress occurs, first causing reductions in leaf and stem expansion and increased partitioning of CH_2O to roots, followed by decreased photosynthesis and transpiration.

Insect Submodel

The corn earworm (Heliothis zea) is extremely polyphagous, attacking a number of crops including corn and soybeans, upon which very large populations can develop, causing extreme defoliation (Neunzig, 1969). Because corn earworm populations can vary markedly from field to field and from year to year, population models developed for this species must be year- and site-specific.

The corn earworm submodel is derived from the population dynamics model of Stinner et al. (1974). In it, populations are divided into six developmental stages: eggs, small larvae, medium larvae, large larvae, pupae, and adults. Larvae are separated by size rather than instar because field identification of instars is often difficult, and separating samples on the basis of size is much easier. The small size class corresponds roughly to larval instars I and II; medium to instars II and IV; and large to the later instars.

In the population model, the age structure (a) is maintained within each developmental stage (i). The change in population density ($N_i = N_i(a,t)$) in each stage can be expressed as:

$$\frac{dN_i}{dt} + \frac{dN_i}{da} = -m_i N_i - TN_i + E_i$$

where: m_i is the stage-specific mortality, T_i is a developmental function, and Ei is the number of insects that enter a stage, either immigrating into the field or developing from the previous stage. For stages small larva to adult (i = 2..6), E_i is the number of insects that make the transition from the previous stage. For the adult stage, E_i includes the immigrating adults also. For eggs, E_i is the total number of eggs ovipositing on day t. E_i, m_i, and T_i are functions of a and t.

The effect of varying temperature is incorporated into the model by calculating physiological days. One physiological day is defined as the proportion of development completed in one day at a reference temperature, taken to be 27°C. For example, at 18°C an average corn earworm requires twice as long to go from egg to adult as it does at 27°C. Thus, one day at 18°C equals 0.5 physiological days. A lower development threshold of 13°C was used (Mangat and Apple, 1966a).

The variability of individual developmental rates within the population was accounted for in the model by using a cumulative distribution function, $F_i(a_p)$, taken from Stinner et al. (1975), where a_p represents physiological age.

The proportion of those insects present at time t of age a, that complete stage i at time t, $T_i(a,t)$, is obtained by differentiating the cumulative distribution function $F_i(a_p)$:

$$T_i\,(a,t) = \frac{F_i[a_p(a,t)]}{1 - F_i[a_p(a,t)]}\,[1 - m_i]$$

The term $[1 - m_i]$ is included because the cumulative distribution function is based on the number that survive a stage and develop into the next.

The total number of eggs laid by a female corn earworm in her lifetime is a function of temperature (Isely, 1935). The proportion of those eggs laid on any particular day is a function of temperature and adult stage (Isely, 1935). Each day, the number of eggs each female lays is calculated from that day's temperature. The eggs are distributed on the plant according to data of Johnson et al. (1975).

Mortalities inflicted by predators, m_{iP}, insecticides, m_{iT}, and food shortages, m_iF, are incorporated into the model explicitly. Functionally, mortality is represented as

$$m_i = 1 - (1 - m_{iB})(1 - m_{iF})(1 - m_{ip})(1 - m_{iT})$$

where m_{iB} represents background mortality due to factors other than predators, insecticides, or food shortages.

For all stages except pupae, background mortality (m_{iB}) is considered to be a constant proportion per day throughout the season: 0.10, 0.05, 0.05, 0.02, 0.05 for eggs, small, medium and large larvae, and adults respectively. Background mortality for pupae is a function of crop leaf area index.

Mortality due to food (m_{iF}) is equal to zero unless leaf area has been zero for at least 2 days. This factor increases linearly thereafter until it reaches 1.0 ten days after leaf area has been zero.

Corn earworm is a migratory insect that overwinters across most of its range as diapausing pupae (Mangat and Apple, 1966a, 1966b). Pupae breaking diapause develop into adults that usually lay the first brood on corn. Later generations invade other crops, including soybeans. The first adults appear in light traps in June or July; larvae are not usually found in soybean fields until early August.

Simulations

SICM was run for Castana, Iowa, for which weather and soil condition data were known for 1979. This site was chosen over several other sites for which data were available, because it is well north of the area where corn earworm is a major pest on soybeans. This Iowa site is also representative of the major grain producing areas in the Midwest. No insecticide was used in the simulations; this defines a baseline for comparison. Insecticide application adds significantly to costs, so the expected return must be enough to cover those costs. The insect population level at which insecticide application becomes desirable is called the economic threshold. Of course this parameter varies with the current price of the commodity, so that the same insect population density on two different occasions may have different economic thresholds. For this reason, the economic environment was also kept constant in all simulations.

Three sets of simulations were performed: the first using actual weather data for Castana, Iowa, in 1979; the second used GISS predictions for a doubling of the CO_2 level; and the third used the GFDL predictions. To obtain predictions for Castana, the weather model outputs were interpolated in both space and time to give expected daily temperature and precipitation changes (Figure 5). The expected changes were then added to the 1979 weather data to create modified weather data files, which were fed into the simulation. The outputs were compared to those from the model using unmodified weather data. The output variables recorded are the date at which the corn earworm population peaked, the peak population, the yield in bushels per hectare, and the profit per hectare.

Results

Table 2 gives a summary of the output from SICM. Using the 1979 weather data (the first block in the table), the corn earworm moths left corn in early August, too late to be a serious pest on soybeans. Even fairly large influxes of corn earworm into soybean have no effect on yield or profit if they are not early, but an early influx does significantly reduce yield and profit. This contrasts with the modified weather scenarios. Not only do the higher summer temperatures and reduced precipitation reduce the yield of this particular cultivar, but they have a synergistic effect on the plant-insect interaction. The major impact of the higher temperatures on insect population is more rapid growth, earlier in the season. This results in a larger, earlier emigration from corn, and a corresponding increase in damage to the soybeans. Interestingly, the two climate scenarios produce quantitatively similar results. Qualitatively, the GFDL scenario is much worse, probably due to its lower predicted summer precipitation. Under no circumstances can a profit be made under the GFDL scenario without insecticide application: the combination of early influx and larger than average numbers completely destroys an already moisture stressed crop. With the GISS scenario, normal and larger than normal influxes have no effect on profitability. But, again, an early influx is devastating.

Caveats

As mentioned in the description of the model, the latitude and temperature regime dictates the soybean cultivar that can be used. In these simulations, cultivar "Wayne" was used throughout. It is an ideal choice for central Iowa for today's conditions, but the simulations show that if the climate does warm, and especially if summer precipitation declines, "Wayne" would be an inappropriate choice. Also, the absence of any insecticide is an unusual situation. Other insects feed on soybeans, against which a farmer would use an insecticide. Thus, the results are not as bleak as they at first appear. They do suggest that an expanded use of insecticide would be inevitable, a point well illustrated by the spider mite outbreak during 1988, during which insecticide use on soybeans increased over tenfold.

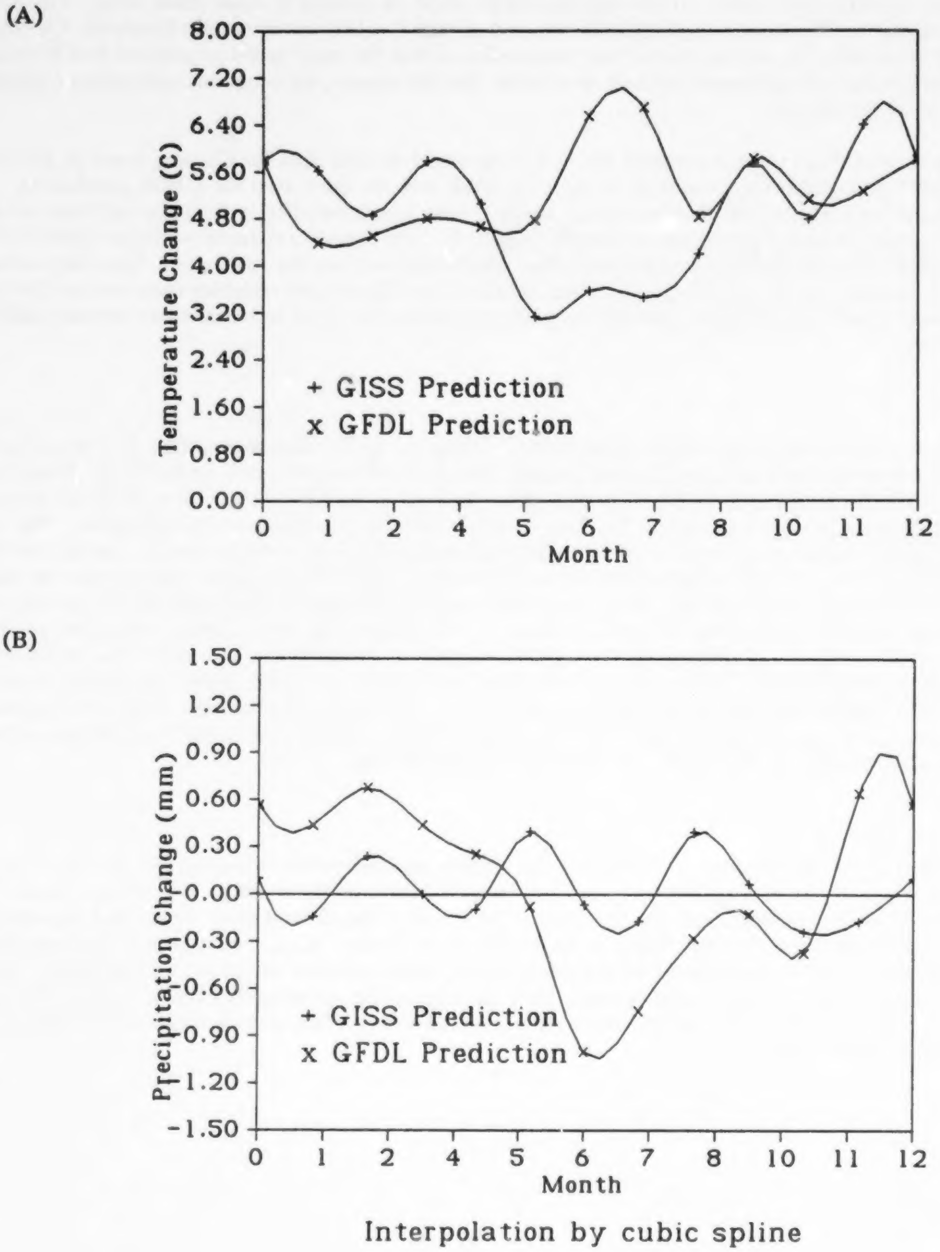

Figure 5. (A) Temperature change and (B) precipitation change in Iowa.

Table 2. Summary of Effects of Climate Change on Soybean-*Heliothis* Interactions

		Influx of *Heliothis zea*:				
Climate Model	Output Variable	None	Normal	Early	Large	Early & Large
NONE	Day of peak	n/a	223	198	223	198
	Larval density	n/a	0.45	58	1.70	230
	Yield (bu/ha)	24	24	22	24	21
	Profit ($/ha)	37	37	27	37	15
GISS	Day of peak	n/a	220	192	220	192
	Larval density	n/a	0.25	81	1	330
	Yield (bu/ha)	20	20	17	20	8
	Profit ($/ha)	11	11	-1	11	-72
GFDL	Day of peak	n/a	223	200	223	200
	Larval density	n/a	0.35	100	1.40	430
	Yield (bu/ha)	10	10	8	10	0
	Profit ($/ha)	-62	-62	-72	-62	-130

ESTIMATES OF LAND USE AND PEST IMPACT CHANGE AS INFLUENCED BY TEMPERATURE AND PRECIPITATION CHANGES

In Table 3, we have summarized the results of regression analysis incorporating temperature and precipitation variables. The objective was to develop a summary of climate change effects on pest severity based upon mean annual temperature changes of 2°C and 4°C.

The major patterns that emerged from this exercise are as follows:

1. Corn acreage decreases with temperature increase.
2. Changes in corn acreage are greater in the southern and western regions than in the northern, more humid areas.
3. Pest severity on corn increased with temperature rise only in the Lake State region, remained unchanged in the Northern Plains and Corn Belt, and decreased in severity in the southern regions.
4. No trend in pathogen severity was observed.
5. Soybean acreage was less affected than corn by temperature change.
6. Pest severity on soybean increased with temperature rise in all regions, but was most marked in the northern areas.
7. Pathogen severity on soybean increased with temperature and most notably in the northern areas.

Table 3. Summary of Current and Projected Scenarios For Land Usage and Percent Yield Loss Due to Pest and Pathogen Damage

SCENARIO TEMP.,PREC.	NORTHERN PLAINS	LAKE STATES	CORN BELT	DELTA STATES	SOUTHEAST STATES	SOUTHERN PLAINS	SUMMARY
MILLIONS OF ACRES - CORN							
CURRENT	13.1	13.9	37.2	2.3	3.2	1.2	70.9
+2, +0	8.9	11.6	31.3	.6	.6	.0	53.0
+4, +0	3.9	7.6	26.6	.0	.0	.0	38.1
+2, +10	10.6	12.8	33.1	1.0	.9	.0	58.4
+4, +20	6.8	10.0	29.2	.2	.1	.0	46.3
PERCENT YIELD LOSS WITHOUT PESTICIDES FROM INSECT PESTS - CORN							
CURRENT	27.0	9.8	27.8	15.3	25.1	15.3	23.4
+2, +0	27.8	11.7	28.2	13.4	23.2	13.4	24.3
+4, +0	27.8	13.6	27.0	11.5	21.3	11.5	24.4
+2, +10	27.5	11.4	27.9	13.1	22.9	13.1	23.9
+4, +20	27.2	13.0	26.4	10.9	20.7	10.9	23.6
PERCENT YIELD LOSS WITHOUT PESTICIDES FROM PATHOGENS - CORN							
CURRENT	13.1	7.6	8.3	7.5	10.9	7.5	9.1
+2, +0	13.1	7.6	8.3	7.5	10.9	7.5	9.0
+4, +0	13.1	7.6	8.3	7.5	10.9	7.5	8.7
+2, +10	12.8	7.3	8.0	7.2	10.6	7.2	8.7
+4, +20	12.5	7.0	7.7	6.9	10.3	6.9	8.3
MILLIONS OF ACRES - SOYBEANS							
CURRENT	5.0	5.9	30.3	14.3	8.4	1.1	65.0
+2, +0	3.4	5.1	28.9	12.1	6.7	.0	56.2
+4, +0	.9	4.0	25.5	10.0	4.9	.0	45.3
+2, +10	6.3	6.6	30.3	14.3	8.4	1.1	67.0
+4, +20	6.3	6.6	30.3	14.3	8.4	1.1	67.0
PERCENT YIELD LOSS WITHOUT PESTICIDES FROM INSECT PESTS - SOYBEANS							
CURRENT	.0	.9	1.8	18.5	61.2	18.5	13.2
+2, +0	3.7	4.0	6.4	23.1	65.8	23.1	16.7
+4, +0	7.4	8.6	11.1	27.8	70.5	27.8	20.9
+2, +10	5.4	6.0	8.5	25.2	67.9	25.2	19.2
+4, +20	11.5	12.7	15.2	31.9	74.6	31.9	25.9
PERCENT YIELD LOSS WITHOUT PESTICIDES FROM PATHOGENS - SOYBEANS							
CURRENT	7.2	2.3	6.3	30.9	12.1	30.9	12.6
+2, +0	10.2	5.3	9.3	33.9	15.1	33.9	15.0
+4, +0	13.3	8.4	12.4	37.0	18.2	37.0	18.1
+2, +10	10.3	5.4	9.4	34.0	15.2	34.0	15.5
+4, +20	13.4	8.5	12.5	37.1	18.3	37.1	18.6

REGIONS: NORTHERN PLAINS = COLORADO, KANSAS, NEBRASKA, NORTH DAKOTA, SOUTH DAKOTA. LAKE STATES = MICHIGAN, MINNESOTA, WISCONSIN. CORN BELT = ILLINOIS, INDIANA, IOWA, MISSOURI, OHIO. DELTA STATES = ARKANSAS, LOUISIANA, KENTUCKY, MISSISSIPPI, TENNESSEE. SOUTHEAST STATES = ALABAMA, GEORGIA, NORTH CAROLINA, SOUTH CAROLINA. SOUTHERN PLAINS = OKLAHOMA, TEXAS. TEMP., PREC. = DEVIATION FROM MEAN ANNUAL TEMPERATURE IN DEGREES C AND FROM TOTAL ANNUAL PRECIPITATION IN CENTIMETERS.

INTERPRETATION OF RESULTS, RESEARCH NEEDS, AND POLICY IMPLICATIONS

For both the literature search on ecological mechanisms and the modeling efforts, both temperature and precipitation patterns were key variables affecting crop-pest interactions. The overall, emerging pattern is that pest severity will increase with the predicted warming patterns and that this effect will be more marked in the higher latitudes. Interactive effects with precipitation patterns are more difficult to discern and depend quite heavily on crop stress phenomena.

If pest damage to crops does increase as predicted, then the consequent economic and environmental ramifications would be substantial. As our modeling indicated, the economic losses due to only one species could be sufficient to remove what is an already small profit margin on field crops. In all probability, pesticides would be effective in at least reducing damage severity. Yet the economic and environmental costs of remedial treatment can also be substantial. Pesticide application would cost up to $20 per acre per treatment. The increased use of pesticides would create an additional threat to ecosystem integrity through soil and water contamination and through the increased risks to public health. The predicted increases in pest severity resulting from climate change would not only cause more intense problems in areas where the pest-crop interactions already occur, but would also lead to economic damage in new areas particularly in the northern farming regions. If the farming community is not to rely increasingly on potentially environmentally damaging chemicals, then there surely will be an increased need for alternative pest management strategies. In terms of policy implications, perhaps the primary take home message is that under the anticipated climate changes, more than ever, there will be a need for intensive support of alternative pest management strategies that utilize a range of tactics, such as biological control, genetic resistance, and innovative cropping systems, instead of increased reliance on chemical toxicants.

Research needs addressing these concerns can be summarized as follows:

1. Carry out targeted studies on the effects of climate change variables on specific pest-crop interactions in controlled and semicontrolled environments.

2. Carry out long-term studies to develop cropping systems that use natural ecological processes to buffer the negative impacts of climate change.

3. Perform modeling studies that examine a range of site- and species-specific interactions.

4. Develop of a better understanding of thermoperiodic response in more pest and potential pest species, so that modeling studies may be performed for more species.

5. Perform integrative modeling studies that incorporate crop, soil, pest and biological control phenomena.

6. Conduct research programs directed toward designing integrative pest management strategies relevant to the climate change scenarios.

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IMPACTS OF CLIMATE CHANGE ON THE TRANSPORT OF AGRICULTURAL CHEMICALS ACROSS THE USA GREAT PLAINS AND CENTRAL PRAIRIE

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FINDINGS[1]

Pesticide pollutants are ranked as a high priority non-point source pollution problem in at least one-half of the states within the U.S. Great Plains and Central Prairie. Potentially toxic agricultural chemicals can be removed from application sites through degradation, surface runoff, sediment transport, and downward percolation. An understanding of the importance of these processes under the present environment, as well as under alternative environmental futures, is essential to the thorough evaluation of potential threats to drinking water quality.

The present study focused on interactions among agricultural soil/tillage/management systems, pesticide transport, and the implications of CO_2 doubling on subsequent water quality in the U.S. Great Plains and Central Prairie. A model which mathematically simulates the vertical and horizontal surface movement of water and its contents across a field and through the crop root zone was applied. The critical parameters supplied to the model included soil profiles, crop phenology, tillage/management practices, and pesticide use. Weather data included mean daily temperature and precipitation.

These parameters were supplied at 26 locations, spanning four cropping regions; spring wheat, winter wheat, cotton, and corn. Each site was characterized by three different soils (sand, silt, clay), three tillage/management systems (conservation, conventional and conventional with crop residues left on the field after harvest), and three classes of pesticides: those which are highly soluble and persistent, relatively insoluble and persistent, and highly soluble but not persistent in the soil. The study is limited to those preplant pesticides applied to the soil surface or applied to the soil surface and shallowly incorporated.

Primary limitations of the model's use in this application include: 1) the sensitivity of the model to the selection of cropping system parameters; 2) no modeling of direct impacts of increased CO_2 on vegetative cover; 3) no modeling of macro-pore or vadose zone transport; 4) the sensitivity of the results to changes in precipitation, whose processes are not well modeled by present GCM's (General Circulation Models); and 5) the care with which regional results must be prepared, interpreted, and applied when derived from a point estimate model.

Statistically significant chemical loading results for each crop region include:

1) Northern Plains (Spring Wheat): Under GFDL-estimated temperature and precipitation conditions, runoff and erosion of highly soluble short-lived pesticides could increase while erosion of less soluble long-lived pesticides could decrease. Leaching of all pesticides could decrease.

2) Central Plains (Winter Wheat): Under GISS-estimated temperature and precipitation conditions, runoff and erosion of all pesticide types studied, on all soils studied, could increase.

3) Southern Plains (Cotton): Under GISS-estimated temperature and precipitation conditions, regional pesticide runoff could increase. Surface erosion of some pesticides could also increase. Under GFDL-estimated temperature and precipitation conditions, surface runoff losses of some pesticides could increase.

4) Central Prairie (Corn): Under GFDL-estimated temperature and precipitation conditions, model-generated regional surface runoff and subsurface leaching of all the chemicals studied declined.

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These results are not forecasts, but represent a range of alternative futures under numerically estimated weather conditions. Another set of model-generated weather outcomes would likely result in a different set of pesticide transport results.

CHAPTER 1

INTRODUCTION

THE PROBLEM: WATER QUALITY IN THE U.S. GREAT PLAINS AND CENTRAL PRAIRIE

Even a brief overview of the status and future of water quality in the Great Plains and Central Prairie can quickly evolve into an extensive treatise. Such matters are important considerations under current climatic conditions and are not expected to disappear.

At least two major documents summarizing nonpoint source pollution information on a state-by-state basis have appeared in recent years: the STEP Report (ASIWPCA, 1984), and the SNAP Report (ASIWPCA, 1985). Based on these ASIWPCA documents, eight of the twelve states in the Great Plains and Central Prairie region consider agricultural nonpoint source pollution to be a major source of their water quality problems (ASIWPCA, 1985). Three other states identified agricultural nonpoint source pollution as a significant problem. The SNAP report indicates that 43% of all river miles assessed and 39% of all lake surface acres assessed sustain at least moderate impacts from agricultural nonpoint source pollution (ASIWPCA, 1985).

Pesticide pollutants, a specific category of agricultural nonpoint pollution, ranked as a high-priority problem in six of the twelve study area states: Illinois, Iowa, Kansas, Oklahoma, South Dakota, and Texas (EPA, 1984). For the U.S. Great Plains and Central Prairie region, the SNAP report indicates that water use of 60,812 surface acres and 21,246 river miles is at least threatened by pesticide pollutants. In this same area, there are more than 200 public and private drinking water wells and more than 45,000 mi^2 of aquifers that are known or suspected to be polluted by pesticides (ASIWPCA, 1985).

Delivery of pesticides to water bodies varies according to crop adsorption characteristics, whether the chemicals are transported as solutes in water or attached to sediment particles, rainfall, slope and soil type, and the proximity of the land to a waterway. Newer pesticides have fewer long-term impacts, but are more likely to be water soluble. Thus, water (rather than sediment) is the primary vehicle by which these chemicals enter water bodies. In most cases, sediment control measures also control runoff water, but concern remains as to whether they provide adequate protection. Water quality impairments resulting from pesticides are related to the toxic effects of pesticides and are due more to concentrations than to total loadings (Maas, et al., 1985). If pesticide application rates are held constant, techniques such as conservation tillage, terraces, and contouring assume that pesticide surface loadings will be reduced by reducing surface runoff volume. However, as a result of decreased dilution these practices may not significantly reduce edge-of-field pesticide concentrations.

In addition to these concerns, toxic water-soluble chemicals in pesticides may be more biologically available when freely waterborne than they are when bound to sediment (EPA, 1984). Thus, they may cause acute short-term surface water impacts and eventually have serious effects on ground water resources through percolation. Two specific case studies in Kansas and Ohio are presented to illustrate the extent of recent pesticide pollution problems in the study region.

Butler and Arruda (1985) report that since 1977, a total of 21 different pesticides have been found above their detection limits in Kansas streams and rivers. Over the period of record (1977-1984), atrazine, alachlor, metolochlor, 2,4-D, and metribuzin have accounted for 77 percent of the total detections. The frequency of detection of these pesticides has increased over time. Water from some of the lakes and certain stream segments with detected pesticides is used for domestic consumption after treatment, and pesticides were found in the treated drinking water.

Baker et al. (1985) studied the effects of intensive agricultural land use on regional water quality in northwestern Ohio. Simazine, atrazine, alachlor, metolachlor, linuron, and cyanazine were found in tap water at Tiffin, Fremont, and Bowling Green, Ohio. Seasonal occurrences of herbicides in stream systems also result in seasonal pesticide exposures in drinking water derived from river systems. Most soluble pesticides pass through conventional water treatment plants with very little attenuation (Baker et al., 1985).

Although long-range policy decisions concerning non-point water pollution begin by considering today's problems, possible future scenarios must also be considered. One set of "possible futures" is derived from the expected impacts of increasing concentrations of CO_2 and other trace gases (Titus, 1986). The task at hand is to assess the potential impacts of numerically derived CO_2-related climate changes on pesticide fate in the Great Plains and Central Prairie.

LITERATURE REVIEW

The impacts of CO_2-doubling climate change on hydrologic aspects of agriculture in the Great Plains have been studied by a number of researchers. Robertson et al. (1987) consider the impacts of climate change on yields and soil erosion for selected crops in the Southern U.S., Central Prairie and Northern Plains using the Erosion Productivity Impact Calculator (EPIC). Mather and Feddema (1986) consider CO_2-doubling-induced hydrologic changes in 12 regions across the globe including the Upper Midwest and Texas. Numerous studies have considered the modeling of pesticide movement independent of climate change (see Donigian et al., 1986; Imhoff et al., 1983; Knisel, 1980; Aller et al., 1985; and Donigian and Carsel, 1985). These studies focus on the development and verification of field or watershed models under a variety of geographic, climatological and agricultural management conditions. Although chemical transport research which explicitly addresses the impacts of CO_2-induced climate change on chemical transport is virtually non-existent, the range of model sensitivity analyses and verification and their use in "what if" type studies provides a logical springboard to climate change applications. An example of such a preliminary study of these impacts across the southern U.S. is Cooter (1987).

PROJECT OVERVIEW

The present study focuses on interactions among agricultural soil/tillage/management systems, pesticide movement, and the potential impacts of CO_2-doubling on subsequent hydrologic quality in the U.S. Great Plains. In this case, the Great Plains is defined as including a northern spring wheat production region, a central winter wheat production region, a southern cotton production region, and a Central Prairie corn production region. The purpose of the research to be presented is neither to defend nor support specific general circulation model results, but to apply the best currently available information to issues of national interest. Although agricultural water quality issues will be addressed, this document does not represent a toxics study. Statements concerning toxicity and chemical concentrations are desirable goals, but the case will be presented that the present state-of-the-art models may be insufficient to support definitive location-specific policy statements.

Weather data from twenty-six National Weather Service (NWS) First Order and cooperative observation stations were used to represent the climates of the study areas. Stations representative of each region were selected on the basis of completeness of record for the period 1951-1980. The selected stations and their proximity to cropping regions are shown in Figure 1. Three generic soil types (all loams) were analyzed at each weather site; sand, silt, and clay. Specific soils were selected to represent each of these three general types (see Table 1). Three general tillages were selected to represent agricultural management in each region: conservation, conventional, and conventional with residue remaining. The conservation tillage management system was taken to be one in which a chisel plow was used. Descriptions of the complete management systems are provided in the methodology portion of this report and are summarized in Table 2.

Given these regional production conditions, a process type chemical transport computer model was run for each station, soil, and tillage combination contained in Figure 1 and Tables 1 and 2. This range of production scenarios facilitates the examination of pesticide movement in terms of the quantity of chemical that could be eroded or washed off the soil into surface water supplies, or that could be leached out of the bottom of the soil profile and thus become available for further vertical or horizontal movement into drinking water supplies.

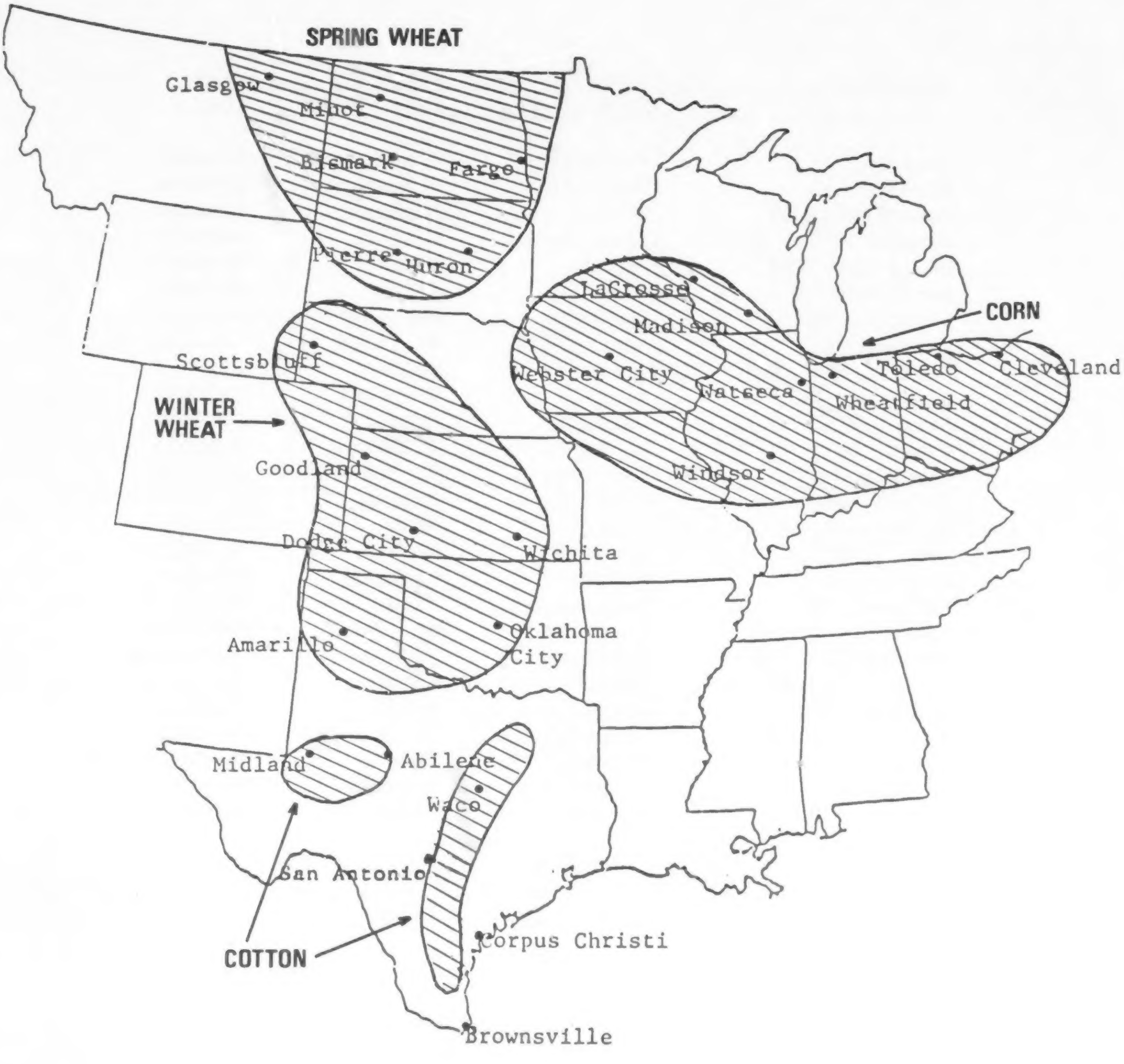
SPRING WHEAT
Glasgow
Minot
Bismark
Fargo
Pierre
Huron
WINTER WHEAT
Scottsbluff
Goodland
Dodge City
Wichita
Amarillo
Oklahoma City
CORN
LaCrosse
Madison
Webster City
Watseca
Windsor
Toledo
Wheatfield
Cleveland
COTTON
Midland
Abilene
Waco
San Antonio
Corpus Christi
Brownsville

Figure 1. Weather stations and cropping areas utilized in the climate change analysis.

Table 1. Sand, Silt, and Clay Loam Soils Selected for Each Site Analysis

STATION	SANDY LOAM	SILTY LOAM	CLAY LOAM
Watseka, IL	Plainfield	Flanagan	Drummer
Windsor, IL	Oakville	Flanagan	Drummer
Wheatfield, IN	Granby	Flanagan	Drummer
Webster City, IA	Plainfield	Clarion	Webster
Dodge City, KS	Pratt	Harney	Nibson
Goodland, KS	Otero	Keith	Nibson
Wichita, KS	Holdrege	Hastings	Garvin
Glasgow, MT	Amor	Williams	Bowdine
Scottsbluff, NE	Otero	Weld	Uly
Bismarck, ND	Amor	Williams	Parnell
Fargo, ND	Emrick	Fargo	Nutley
Minot, ND	Hecla	Williams	Parnell
Cleveland, OH	Red Hook	Spinks	Sebring
Toledo, OH	Rocky Ford	Tappan	Ellsworth
Oklahoma City, OK	Pratt	Grant	Garvin
Huron, SD	Embden	Clarno	Parnell
Pierre, SD	Embden	Glenham	Promise
Abilene, TX	Waldeck	Miles	Foard
Amarillo, TX	Amarillo	St. Paul	Pullman
Brownsville, TX	Delfina	Hidalgo	Harlingen
Corpus Christi, TX	Segno	Norwood	Beaumont
Midland, TX	Amarillo	Acuff	Pullman
San Antonio, TX	Crockett	Venus	Heiden
Waco, TX	Crockett	Bosque	Houston-Blac
La Crosse, WI	Plainfield	Fayette	Clyde
Madison, WI	Coloma	Plano	Reddick

Table 2. Continuous cropping tillage//management systems for each crop and region used as input to PRZM. All chemicals applied at planting. (T_o = surface soil temperature.)

CROP	TILLAGE METHOD	TILLAGE OPERATION	RESIDUE OR NO RESIDUE	PLANTING DATE	PLANTING CRITERIA	HARVEST (DAYS FROM PLANT)
Spring Wheat	Conservation	Chisel Plow	No Residue	April 1-May 30	$T_o > 21°C$	135
	Conventional	Moldboard	Residue			
	Conventional	Moldboard	No Residue			
Winter Wheat	Conservation	Chisel Plow	No Residue	Sept 15-Oct 15	Previous 7-day precipitation > 2.54 cm Soil moisture < field capacity	249 (Texas and Oklahoma) 267 (Kansas) 293 (Nebraska)
	Conventional	Moldboard	Residue			
	Conventional	Moldboard	No Residue			
Cotton	Conservation	Chisel Plow	No Residue	March 1-June 25	$T_o > 28.3°C$ Soil moisture < field capacity	165
	Conventional	Moldboard	No Residue			
	*Conventional	Moldboard	Residue			
Corn	Conservation	Chisel Plow	No Residue	April 1-June 15	$T_o > 21°C$ Soil moisture < field capacity	165
	Conventional	Fall Moldboard	No Residue			
	Conventional	Spring Moldboard	Residue			

* This management scenario is not practiced in the cotton study area at present. The scenario was included to examine possible implications of its future use.

Major research results are presented in terms of direction and magnitude of regional changes in levels of pesticide losses to surface runoff, erosion, and subsurface leaching. Secondary discussions of within region and inter-scenario variability are presented to reinforce discussions of model limitations and result interpretation (Appendices A and B). The remainder of this report describes the modeling methodology applied and its limitations, presents and interprets the results, and addresses the environmental and socioeconomic implications of these results.

THE STUDY REGION

Norum et al. (1957) propose that the most compelling fact of agriculture in the cool, temperate Northern Great Plains is the irregular and generally deficient rainfall. They conclude that the climate, topography, soil and native vegetation of the area comprising North Dakota, South Dakota, and the sand hills region of Nebraska encourage a cropping agriculture broadly devoted to the production of spring wheat. The spring wheat production area extends from the Red River Valley westward and southward to the range country of Montana and South Dakota and includes mainly loamy and sandy soils developed on varied glacial deposits. An area of several counties in north central Montana has soil and topography favorable for production of spring wheat, although rangeland separates it from the major spring wheat area. With precipitation low relative to evaporation and transpiration, unevenly distributed seasonally, and possessing great interannual variability, small negative deviations in precipitation are sufficient to initiate a condition of drought. Negative deviations, small and large, are frequent in these regions (Rosenberg, 1980).

South of the Northern High Plains is a region in which winter wheat production predominates. This area comprises Kansas, southwestern Nebraska, and the northwestern one-third of Oklahoma (Hobbs, 1957). There is considerable variation in temperature and precipitation across this region. Annual precipitation ranges from 38 inches in the southeast to 14 inches along the western edge. The frost-free growing season ranges from more than 210 days in the southeast to fewer than 140 days in the northwest. Many marginal soils exist but they are generally productive and respond well to good management (Hobbs, 1957). The main problems are the irregularity of precipitation, the need for supplemental fertilization, and water and wind erosion. Water erosion may result in sizable soil losses from sloping fields in this area. Areas of sandy soils are extensive in southwestern Kansas, and the Panhandles of Oklahoma and Texas. Many have a low content of clay in the surface layers and are particularly erosive when they are cultivated.

The southernmost region to be considered comprises the Southern High Plains and Blacklands areas of Texas. Cotton is a major cash crop, and growing it is a highly developed, mechanized enterprise (Johnston, 1957; USDC, 1985). The topography varies from nearly level to strongly rolling. Surface drainage is well developed, except in the part of the region that is on the Southern High Plains. The soils range from slightly acid to calcareous and from deep sands and clays to thin soils. These productive soils absorb moisture quickly, have good water holding ability, and are easily worked. The sandier sections are subject to severe wind erosion. Extreme variations in seasonal and yearly precipitation make year-to-year production uncertain. Such variations in precipitation are more pronounced in the western part of the region than in the east. Extreme variations in temperature sometimes do great damage to crops.

The final study area (Central Prairie) comprises substantial portions of the Corn Belt including northern Illinois, eastern and north central Iowa, and south central Minnesota. Corn is the crop of greatest overall economic importance in this region. Most of the land is level to gently rolling (Pierre and Riecken, 1957). The soils are generally medium to fine in texture. They have good structure and hold moisture well. More than 25 percent of the soils of this Central Prairie subregion are of level to nearly level topography and usually require artificial drainage. Associated with the level soils in many places are soils of moderate slope and good natural drainage. These soils are apt to erode because of their topography when they are cropped intensively. Excessive tillage, especially for corn, has been partly responsible for a decline in soil organic matter, a deterioration of tilth, and an increase in soil erosion (Pierre and Riecken, 1957).

CHAPTER 2

METHODOLOGY

THE EFFECTS MODEL

Development of the Modeling System

The model requirements for the present study include wide geographic applicability, ease of calibration so that results at many locations and under many initial conditions can be examined rapidly, use of environmental parameters that are part of the climate change model output, availability of non-climate input parameters, and inclusion of farm management options so that the role of on-farm response to climate change can be included.

Haan et al. (1982) provide an annotated bibliography of 80 watershed models developed prior to 1978. Of these, only one explicitly addresses pesticide-soil interactions (Agricultural Runoff Management Model (ARM), Crawford and Donigian, 1973). ARM simulation performance is compared with the Cornell Pesticide Model (CPM) in Steenhuis (1979). Other recent watershed models that include chemical transport but were not summarized by Haan are CREAMS (Knisel, 1980), CADIL (Emerson et al., 1984) and HSPF (Johanson et al., 1984).

Dean et al. (1984) review a survey of 50 chemical transport models. They consider in detail SEGOL (Segol, 1976), SUMATRA-1 (van Genchten, 1978), TARGET (Sharma, 1979), and FEMWATER/FEMWASTE (Yeh and Ward, 1980, 1981). In addition, the authors consider the PESTAN (Enfield et al., 1982) and PRZM (Carsel et al., 1984) models. PRZM was selected over the others for use in the regional Leaching Evaluation of Agricultural Chemicals (LEACH) study because of its link to the SCS curve number approach for surface hydrology to supply infiltration volumes, and its ability to be operated quite inexpensively for long simulation time periods (Dean et al., 1984).

PRZM has also been selected for the present study because of its flexibility, accessibility, and ease of use. It meets fully the stated selection criteria, including validation under a wide variety of farm management situations. It is a dynamic, compartmental model which mathematically simulates the movement of water and its dissolved constituents (pesticides) through the upper soil profile, which includes the active root zone of growing crops. The model considers parameterized pesticide-soil and pesticide-water interactions. Rainfall is partitioned into interception (by plants), runoff, and infiltration components based on the Soil Conservation Service curve number technique. Erosion, crop growth, evapotranspiration, and chemical interactions are all simulated or parameterized. Figure 2 provides a schematic view of the simulated processes. The model is described in detail in Carsel et al. (1984).

Field level validation of PRZM has been performed and is documented in Donigian et al. (1986). The application of results from a field-level model to a region surrounding a weather site assumes that the same processes that take place on a 1-ha field take place on many fields throughout the region. No spatial aggregation of PRZM results is performed in this research. All PRZM values are expressed as quantity lost/unit area/year.

The careful selection of representative regional input parameters is essential. The critical parameters supplied to the model for the present application include weather, soil profiles, crop phenology, tillage/management practices, and pesticide characteristics. Many of these parameters are used by PRZM to modify rainfall partitioning to runoff and infiltration and, consequently, the distribution and transport of pesticide within and out of the soil profile.

Climatological input values include mean daily temperature, 24-hour precipitation, and storm duration interval. PRZM assumes that all precipitation reported for a day is delivered by a single storm. As a result,

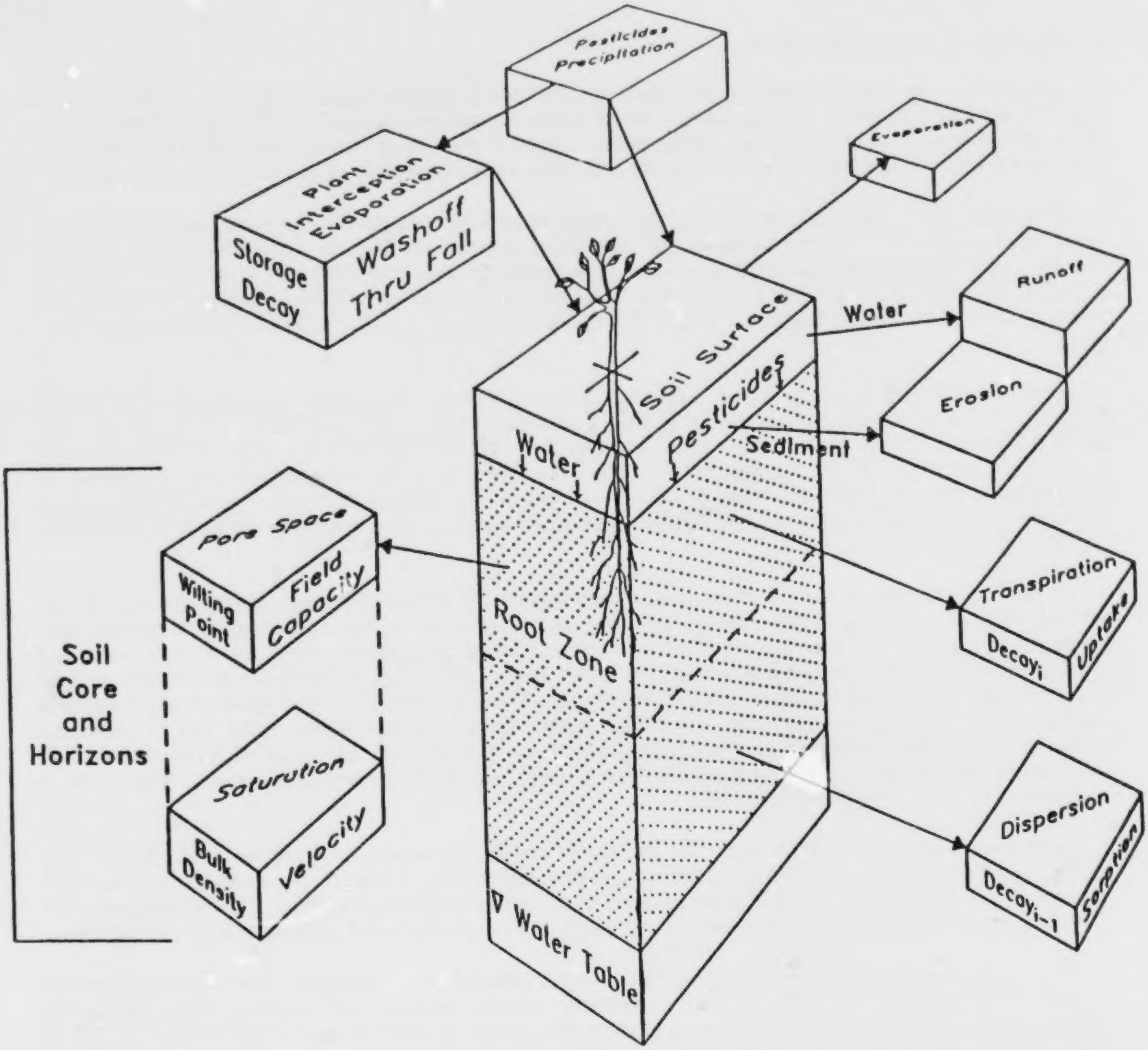
Pesticides
Precipitation
Plant
Interception
Evaporation
Storage
Decay
Washoff
Thru Fall
Evaporation
Soil Surface
Pesticides
Water
Water
Runoff
Sediment
Erosion
Soil
Core
and
Horizons
Pore Space
Wilting
Point
Field
Capacity
Saturation
Bulk
Density
Velocity
Root Zone
Transpiration
Decay$_i$
Uptake
Dispersion
Decay$_{i-1}$
Sorption
∇ Water Table

Figure 2. Schematic of pesticide root zone model (from Carsel et al., 1984).

large 24-hour precipitation reports result in the simulation of more intense rainfall than smaller daily observations. The same storm duration is assumed for all storm events. It is further assumed that the majority of surface losses will be associated with storms which occur near planting, and it is the characteristics of these storms that are used to define storm intensity.

The selection of specific sand, silt, and clay soils assigned to each weather site was based on the greater soil groups contained in "USDA/SCS Land Resource Regions and Major Land Resource Areas of the U.S." (1981), and the short verbal description of each soil contained within the Erosion Productivity Impact Calculator (EPIC) soils data base (Grassland, Soil, and Water Research Laboratory, Temple, TX). Once the soil is selected, soil parameters required as input to PRZM for each layer include: depth (cm), bulk density (g/cm^3), wilting point moisture content (cm^3 of water/cm^3 of soil), field capacity (cm^3 of water/cm^3 of soil), percent organic carbon content, and the universal soil loss equation K value for the profile. Values for these parameters are provided by the EPIC soils data base.

Crop phenology is modeled in PRZM by a fixed second-order polynomial function. Because of this, within-season PRZM phenology estimates are not always representative. When PRZM is linked to process-type yield models, the estimated phenology is usually replaced by that predicted by the crop model (Johnson, 1986; Cooter, 1986). In its original form, PRZM requires specified dates of emergence, maturity, and harvest. PRZM uses these values to adjust parameters such as the daily runoff curve number (bare soil or full cover), crop interception, and root depth.

Planting date can affect the entire pesticide system if it is assumed that pesticides are applied at that time. As soon as the pesticide is applied it can be affected by the environment. If a fixed or unrealistic planting date is provided to PRZM, the model could produce unrepresentative distributions of pesticide wash-off, runoff, or leaching. For the present study, simple conditional algorithms are applied within fixed planting windows to estimate dates of planting. Emergence was set to occur 15 days after the estimated planting date for all crops. Harvest dates were modified to allow for geographic variability across crop regions with large latitudinal ranges (Table 2) (Nuttonson, 1955).

Tillage practices are listed by cropping region in Table 2. Each element of the tillage/management practice implies some modification to the soil water runoff curve, CN. The PRZM users manual provides appropriate parameter estimates for each tillage management combination.

The last group of PRZM input parameters are those associated with the pesticides to be monitored. Rather than attempt to deal with individual pesticides, three classes of pesticide are considered: 1) highly soluble/long-lived (ex. metolochlor, atrazine); 2) highly soluble/short-lived (ex. metribuzin); and 3) slightly soluble/long-lived (ex. trifluralin). The organic carbon distribution coefficient K_{oc} is an inverse indicator of solubility. In this study, high solubility is characterized by K_{oc} values of less than 100. Low solubility is characterized by K_{oc} values greater than 500. Long residence is defined as a chemical half-life in soil of about 140 days. Short residence is defined as a chemical half-life in soil of about 14 days. These combinations of characteristics are most likely to result in undesirable chemicals reaching surface and groundwater systems. For example, in the case of a highly soluble, long-residence pesticide, high solubility permits the chemical to mix readily with surrounding water, which would facilitate its further transport beyond the application site in surface runoff. A long residence time implies a slow rate of chemical degradation. Once the chemical enters the hydrologic system, it will tend to persist for an extended period of time. This increases the likelihood that undesirable chemicals could remain intact long enough to reach major surface or groundwater bodies.

PRZM permits a wide range of pesticide application rates and methods. The model pesticides in this study are applied in field furrows once a year, at planting, at a rate of 1.12 kg/ha (1 lb/ac), or are surface banded or banded and incorporated into the soil to a depth of 5 cm. Wauchope (1978) indicates this is a reasonable application rate, but more than one application may be made per year. This application scenario is most appropriate for spray or granular preplant herbicides or soil insecticides used under all but no-till conditions. Additional simulations are necessary to estimate foliar applied pesticide transport.

Further Limitations of the Model

There are several limitations to the use of the PRZM model in climate change applications. For example, the PRZM ground cover and interception estimates do not take into account the direct effects of increased atmospheric CO_2 on the efficiency of crop biomass production (Baker et al., 1982). Neither does PRZM consider the climate change effect on length of growing season (Newman, 1982). These impacts are important because ground cover (crop/no crop) and leaf area index are used by PRZM to modify the partitioning of rainfall into runoff and infiltration.

Second, PRZM is a one-dimensional(z) flow model. No subsurface lateral flow is computed. Although this can result in an overstatement of recharge and subsequent leaching, long-term trends and qualitative comparisons should remain consistent with field observations. PRZM does not model macro-pore transport. Transport below the root zone can be estimated but has not been verified and so was not used in the present study.

Although the PRZM model has been validated under many environmental conditions and geographic locations, there are certain limitations to its hydrologic budget, particularly in the estimation of recharge. The model performs best in well-drained soil conditions typical of most large-scale U.S. commercial agriculture. It does not perform well under poorly drained or ponding conditions such as those favorable to rice or cranberry production.

Finally, the rate of pesticide decay is directly proportional to temperature. The higher the temperature, the more rapid the decay. PRZM assumes a constant rate of chemical decay. Under a climate change scenario which includes atmospheric warming and, consequently, increased soil temperatures, this could result in overestimates of chemical persistence.

In summary, the most serious limitations to the use of PRZM in the present study are: 1) the need for careful selection of cropping system parameters and the sensitivity of the model to these parameters; 2) the lack of CO_2 doubling impacts on biomass for ground cover; 3) the lack of subsurface horizontal or vadose zone transport; 4) the lack of chemical decay rate response to temperature; and 5) the care with which regional results are prepared, interpreted, and applied when based on a point estimate model.

THE CLIMATE CHANGE SCENARIOS

Scenarios Used

A 30-year time-series of weather data was supplied for each study site in Figure 1. Daily values of historical temperature and precipitation for the period 1951-1980 are used to represent the "base" weather scenario (McDonald et al., 1983). These data are 24-hour summaries of daily values for stations contained in the NWS First Order and Cooperative Meteorological Observation Networks. Although generally complete, these station data often contain missing observations. A statistical interpolation in space and time using nearby stations has been performed to replace missing observations with statistically representative values (Eddy, 1985). Daily data were then modified according to estimated monthly temperature and precipitation changes based on $2xCO_2$ results from each of two global climate models (GCM), GISS (Hanson et al., 1986) and GFDL (Manabe and Weatherald, 1980). This was done by multiplying daily precipitation by a monthly precipitation factor, or by adding a monthly daily temperature change to daily mean temperature values. GCM model output represents the impacts of CO_2 doubling on weather variables at the center of 8° lat x 10° lon grid boxes for GISS and 4.5° lat x 7.5° lon grid boxes for GFDL. No spatial interpolation of the grid box centroid values was performed. Model results are presented and discussed in terms of the base (historical weather) scenario and $2xCO_2$-induced changes from this base.

Issues Resulting from the Climate Scenario

One issue not easily resolved is the use of results generated by models of differing scale. In the case of the GCM's, point manifestations (weather sites) are inferred from a regional (grid box) generalization. In the case of PRZM, regional trends are inferred from a point model. In the present study, it is assumed that the GCMs are addressing large-scale changes in weather parameters. Smaller scale (within region) variability is assumed to remain unchanged from the historical record. Although temperature change limitations are of some concern to PRZM, limitations related to the representation of precipitation by the GCM's are far greater.

Sufficient GCM data are not available to ascertain $2xCO_2$-induced changes in storm frequency or duration resulting from changes in the rainfall delivery system from convective showers to warm frontal rain, or vice versa. Since runoff and erosion are single-storm event processes, this is a serious shortcoming of the induced climate change scenario and limits the time scale appropriate for analysis of results to one or more 24-hour periods rather than to a rainfall event.

The present GCM output requires that the time sequences of the occurrence of precipitation are left unchanged from those of the base scenario data set. Under these conditions, estimates of total annual erosion could easily underestimate the magnitude of the problem in any given year. On the other hand, since a single percentage adjustment is applied to all 24-hour precipitation events within a month, the magnitude of extreme rainfall events is exaggerated. This exaggeration can result in changes in the correlation of temperature and precipitation fields and could result in an overestimation of surface and subsurface pesticide losses in an individual year. Hence, the presentation and interpretation of model-generated results must be pursued with caution.

RESULTS

REGIONAL RESULTS AND INTERPRETATION

Major research findings are presented over a broad geographic scale in qualitative terms. In the absence of an objective means of assessing the validity of GCM environmental projections, consensus impact results may suggest those physical processes or geographic areas that are relatively insensitive to the precise manner of temperature or precipitation estimation. For instance, if both GCM model estimates result in declines of regional pesticide leaching, the implication is that the "signal" of a leaching decrease is stronger than the "noise" created by the application of weather changes estimated under differing GCM assumptions and methods of computation. Consensus directional results are, then, statistically robust. Table 3 summarizes the consensus of direction of change in median values over the base between GISS and GFDL climate change scenarios. Blanks in Table 3 indicate no consensus.

The model output contained in Table 3 indicates that the consensus is that surface pesticide erosion and subsurface leaching could decrease in the northern spring-wheat region of the Great Plains. Central Plains surface changes are scattered, but model output indicates that short-lived pesticide leaching could increase and long-lived pesticide leaching could decrease. Surface runoff and erosion of all pesticide types on all soil types could increase in the southern Great Plains. Short-lived pesticide leaching on silt soils is modeled as increasing and longer lived pesticide leaching on clay soils is modeled as decreasing in this region. All pesticide transport (surface and subsurface) could be decreased in the Central Prairie corn region.

When further regional studies of the scenarios listed in Table 3 were performed, it was found that distributions of certain model predicted changes are significantly different (statistically) from the base case distributions as well as possessing medians for which there is directional consensus across the models (Table 4). In several cases, although there is consensus as to direction of change, the results do not appear to be statistically significant. This is largely the result of the statistical nature of the model results. Model-estimated values of pesticide transport are highly variable and their frequency distributions are skewed towards zero; that is, there are many more small values than large ones. A discussion of these characteristics is provided in Appendix A,

Table 3. Summary of GCM Model Consensus of PRZM Pesticide Transport by Cropping Region, Pesticide, and Soil (+ indicates Median Values Increase Under Climate Change; - Indicates Median Values Decrease Under Climate Change, Blank Indicates No Consensus Among Median Values)

	SURFACE PESTICIDE RUNOFF LOSSES	SURFACE PESTICIDE EROSION LOSSES	PESTICIDE LEACHING
SPRING WHEAT:			
Region(all soils, pesticide, tillage scenarios)		+	-
*Highly Soluble/Short-Lived	+	+	-
Highly Soluble/Long-Lived		+	-
Slightly Soluble/Long-Lived			-
**Clay	+		-
Sand			
Silt	-		-
WINTER WHEAT:			
Region(all soil, pesticide, tillage scenarios)			-
Highly Soluble/Short-Lived		+	+
Highly Soluble/Long-Lived	+		-
Slightly Soluble/Long-Lived			-
Clay	+		
Sand		+	
Silt			
COTTON:			
Region(all soil, pesticide, tillage scenarios)			
Highly Soluble/Short-Lived	+		+
Highly Soluble/Long Lived	+	+	-
Slightly Soluble/Long-Lived	+	+	-
Clay	+	+	-
Sand	+		
Silt	+	+	+
CORN:			
Region(all soil, pesticide, tillage scenarios)		-	-
Highly Soluble/Short-Lived	-	-	
Highly Soluble/Long-Lived		-	-
Slightly Soluble/Long-Lived	-	-	-
Clay			-
Sand			-
Silt		-	-

* ex. Median value of all tillage, soil, weather site, scenarios for highly soluble/short-lived pesticides in the spring wheat crop area.

** ex. Median value of all tillage, pesticide, weather site scenarios for clay soils in the spring wheat crop area.

Table 4. Statistically Significant* Climate Change Impacts on Pesticide Transport Across the USA Great Plains and Central Prairie

Spring Wheat:	Under GFDL estimated temperature and precipitation conditions, runoff and leaching of relatively insoluble long-lived pesticides could decrease as could leaching of highly soluble long-lived pesticides. There are no statistically significant changes under GISS climate change.
Winter Wheat:	Under GISS estimated temperature and precipitation conditions, runoff and erosion losses of all pesticide types studied on all soils could increase. There are no statistically significant changes under GFDL climate change.
Cotton:	Under GISS estimated temperature and precipitation conditions, regional runoff could increase. Runoff of highly soluble short-lived, and relatively insoluble long-lived pesticides could increase. Surface erosion of highly soluble short-lived pesticides could increase. Under GFDL estimated temperature and precipitation conditions, surface runoff of relatively insoluble long-lived pesticides could increase.
Corn:	Under GFDL estimated temperature and precipitation conditions, regional surface runoff and subsurface leaching of the chemicals studied declined. Surface runoff of highly soluble long-lived chemicals declines as does leaching of highly soluble short-lived chemicals. There are no statistically significant changes under GISS climate change.

* The null hypothesis is that there is no difference between the population of pesticide transport results under historical or climate change conditions. A result is declared statistically significant if there is less than a 10% chance that a significant difference has been detected when there really is no significant difference.

but the important implications are: 1) statistics such as mean and standard deviation are not good descriptive measures for pesticide transport; 2) any analysis for policy implications should consider extremes and spread of possible outcomes; and 3) careful stratification of results and use of non-parametric tests may prove helpful in identifying statistically significant double CO_2 impact "signals" from background "noise" generated by different fields, soils, tillages, pesticides, and GCM constraints.

A final result stems from a more detailed regional analysis provided in Appendix B and summarized by Figure 3. Each transport variable analyzed for this study is presented as a percentage of the base or historical case (base = 100%) and is a function of GCM weather scenario and region. For pesticide lost through runoff transport, the most striking impact is the 100% increase over base conditions under GISS climate change conditions in the winter wheat growing season. For pesticide erosion which is, in general, at least one order of magnitude less than pesticide lost through runoff, large increases are noted under the GISS scenario in the winter wheat and cotton growing regions. For pesticide leaching, very large declines are noted under GISS in the spring wheat area, and under GFDL in the corn area. Moderate declines are noted for winter wheat and cotton areas under the GFDL.

A detailed analysis of the temperature and precipitation sources of the changes noted in Tables 3 and 4 and Figure 3 are discussed in some detail in Appendix B. These results generally stem from higher daily temperatures and changes in the amount and timing of precipitation falling on the simulated field. Both GCM's indicate significant temperature increases under double CO_2, but disagree on the pattern of precipitation delivery. This, in large part, accounts for the blank entries indicating no pesticide transport consensus in Table 3. Increased annual pesticide lost in runoff and erosion stem from precipitation increases at planting time, especially in the winter wheat area under the GISS scenario conditions, or increased precipitation during fallow periods.

Areas in which runoff and erosion decline suggest that precipitation changes (increases) were not adequate to overcome increased moisture demands from warmer temperatures or that the large monthly precipitation increases occur at times less favorable for significant pesticide losses. Leaching declines can result from either temperature or precipitation changes. Given constant frequencies, precipitation increases over base conditions can result in higher PRZM estimated soil and adhered pesticide losses via the Modified Universal Soil Loss Equation (MUSLE). If higher than base case soil moistures result from modeled precipitation increases, PRZM modifies the runoff curve number (CN) to partition a larger percent of subsequent rainfall to runoff. This generates greater subsequent losses of pesticides carried by surface runoff. These two processes result in less pesticide remaining to be leached downward through the soil profile. A second contributing factor is higher than base case daytime temperatures which result in greater evaporative demand from the soil. Less moisture is then available in the profile to transport pesticides downward. This can result in less pesticide being leached below the root zone and a larger proportion of the pesticide being stranded in the profile to eventually decay into inactive constituents. Even greater leaching declines are anticipated if the effect of higher soil temperatures on rate of chemical decay had been considered. In most cases, decay rates increase as temperatures rise. Since the chemical decay rate is a constant in PRZM, the model may overestimate the quantity of leachable pesticide in the profile under CO_2 warming conditions. It is most likely that the regional impacts summarized in Figure 3 result from a combination of temperature increases and precipitation intensity changes. Further sensitivity analyses could establish the point at which one factor (temperature or precipitation) overwhelms the other.

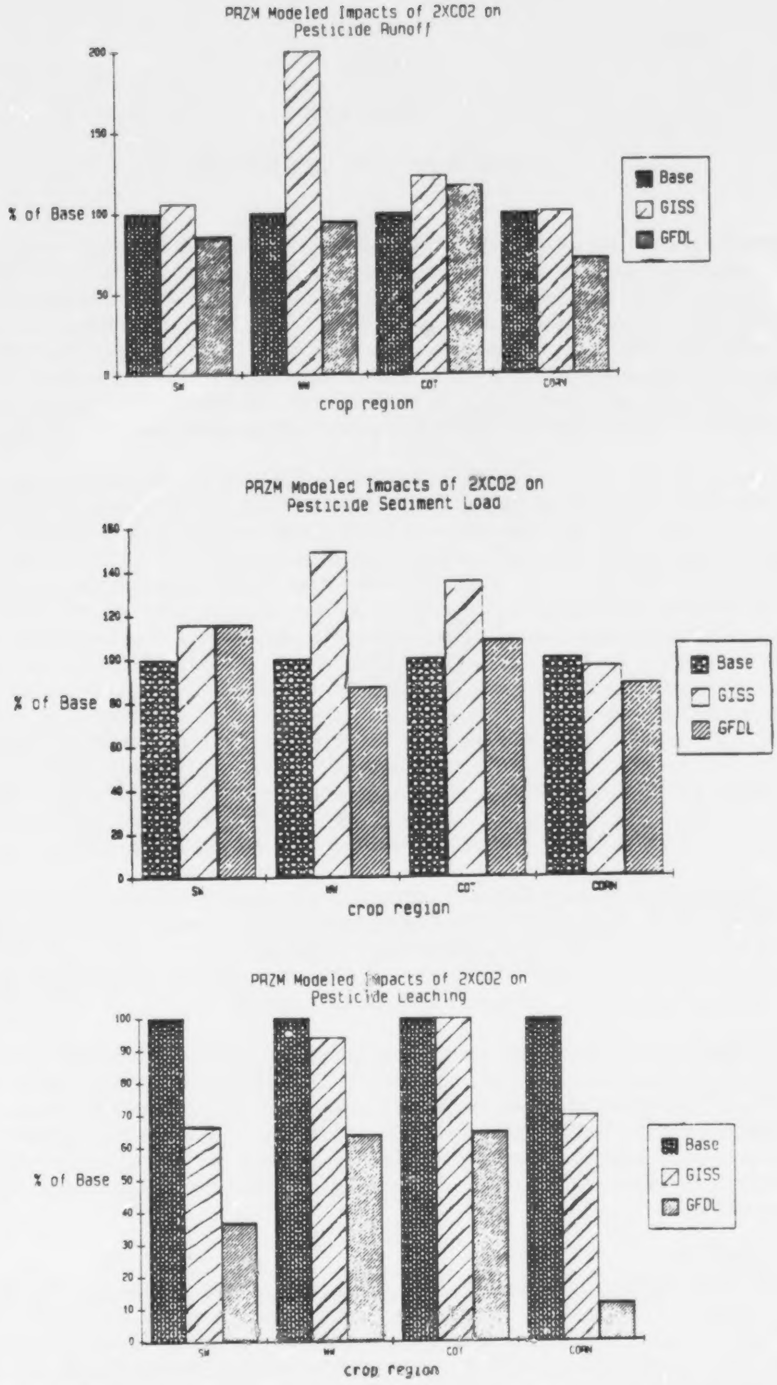

Figure 3. Regional summary of surface and subsurface pesticide loss as a percentage of the base weather scenario losses (base = 100%, SW = Spring Wheat, WW = Winter Wheat, COT = Cotton, CORN = corn).

CHAPTER 3

IMPLICATIONS OF RESULTS

Figures 4 and 5 represent summaries of PRZM results under observed, historical weather for soils which have the greatest chemical erosion potential and the greatest leaching potential. Soil erodability is based on Soil Conservation Service (SCS) class/sub-class designation. Under this system, a designation of 2E indicates a slightly erodable soil. 6E indicates a severely erodable soil. The soils selected for this study had SCS designations of 4E, 5E, or 6E. Only scenarios in Table 2 that include conservation tillage practices were selected for the maximum erosion and leaching studies. This assumes that the farmer realizes there may be erosion problems on his property and is attempting to minimize his soil losses. The specific sandy type EPIC soil selected at a particular analysis site was assumed to possess the greatest leaching potential.

Figures 4a-c contain the areas of greatest model-indicated 30-year median pesticide surface losses under the base weather scenario. Figure 4a highlights those areas in which surface losses of highly soluble short-lived pesticides are the greatest. This area comprises the Texas cotton cropping areas and Oklahoma. Median annual chemical losses (loadings) at sites within this area range from 2.0×10^4 to 9.0×10^4 mg of pesticide lost/ha/yr. Maximum storm event concentrations can be calculated from PRZM output parameters. The distribution of maximum storm event concentrations for each of the 30 base scenario years was computed at Corpus Christi, Texas. These concentration values are compared to sample experimental site observations found in Wauchope (1978) and are presented in Table 5. Although the experimental site values contained in Table 5 fall within the range of values obtained from PRZM simulations for Corpus Christi, the simulated concentrations tend to be high. Wauchope (1978) comments, "Pesticide concentrations in runoff may vary by an order of magnitude or more during a single runoff event, and even event averages for a given chemical are almost unique for each situation, depending on rate of application, storm intensity and timing, field site, etc." Given these comments, the PRZM limitations in terms of precipitation event modeling on a time scale less than 1 day, variations between specific chemicals within the generic group of more than an order of magnitude, and uncertainty in estimates of pesticide properties such as half-life, the PRZM model outcome is remarkably good.

Figure 4b highlights those areas in which surface losses of highly soluble/long-lived pesticides were the greatest. This area comprises the Texas cotton areas, Ohio, western Kansas, South Dakota, and southeastern North Dakota. Median annual chemical losses at sites within this area range from 3.0×10^4 to 2.0×10^5 mg of pesticide lost/ha/yr. Representative PRZM-estimated pesticide runoff concentration and percent pesticide losses at Cleveland, Ohio, were compared to experimental data (Table 5).

Figure 4c highlights those areas in which surface losses of slightly soluble/long-lived pesticides were greatest. The area comprises Texas, Oklahoma and Ohio. Median loading values at the sites within this area range from 2.0×10^4 to 1.8×10^5 mg of pesticide lost/ha/year. Corpus Christi, Texas was again used as a comparison site for experimental runoff concentration and percentage loss results. The Table 5 comparison of this case was the poorest of the three generic groups addressed. Future studies might include a more careful examination of the chemical parameters chosed to represent this generic group and consideration of a range of experimental results rather than a single case.

Figures 5a-b illustrate the areas of PRZM-estimated maximum median annual pesticide leaching under base scenario climatological conditions. Figure 5a summarizes areas of maximum leaching of highly soluble/short-lived as well as slightly soluble/long-lived pesticides. Although areas of maximum leaching are the same for these pesticide types, the quantity of slightly soluble/long-lived pesticide leached is approximately twice that of highly soluble/short-lived pesticide at some locations. Maximum median quantities of highly soluble short-lived pesticide range from 3.7×10^3 mg/ha/yr to 3.0×10^5 mg/ha/year. Maximum median quantities of slightly soluble/long-lived pesticides range from 335 mg/ha/yr to 4.4×10^4 mg/ha/year.

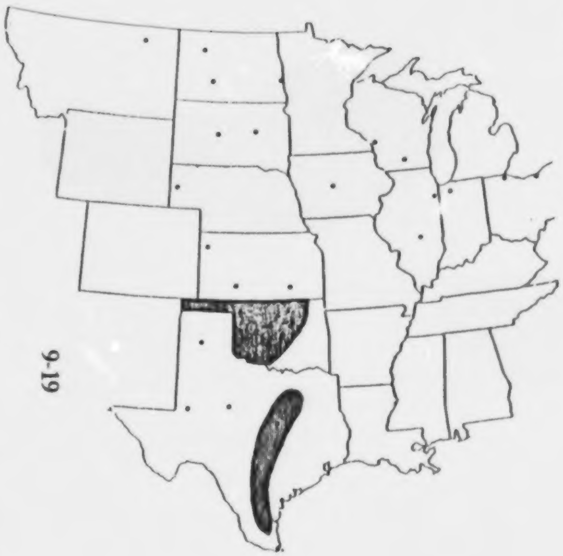

Figure 4a. PRZM modeled areas of maximum potential 30-year median annual pesticide runoff and erosion for highly soluble/short-lived pesticides under historical (base) weather conditions (runoff + erosion > 20,000 mg/ha/yr).

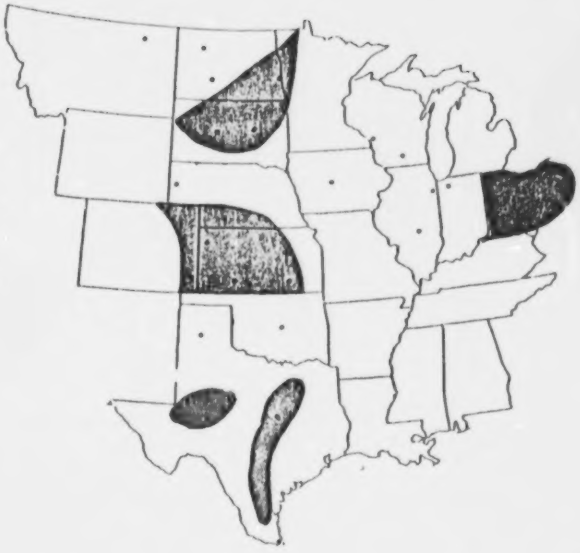

Figure 4b. PRZM modeled areas of maximum potential 30-year median annual pesticide runoff and erosion for highly soluble/long-lived pesticides under historical (base) weather conditions (runoff + erosion > 30,000 mg/ha/yr).

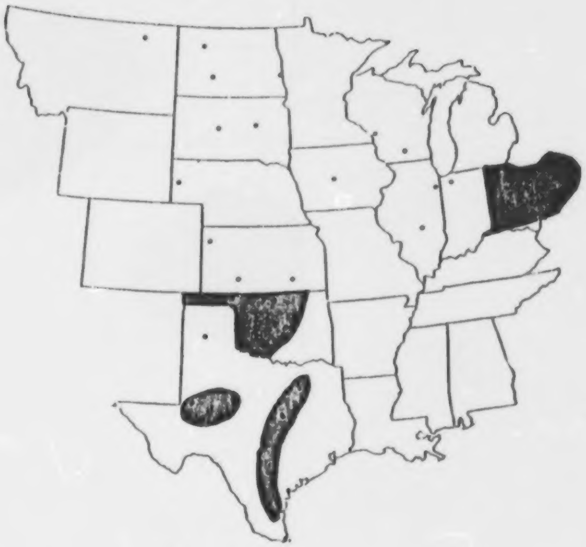

Figure 4c. PRZM modeled areas of maximum potential 30-year median annual pesticide runoff and erosion for slightly soluble/long-lived pesticides under historical (base) weather conditions (runoff + erosion > 20,000 mg/ha/yr).

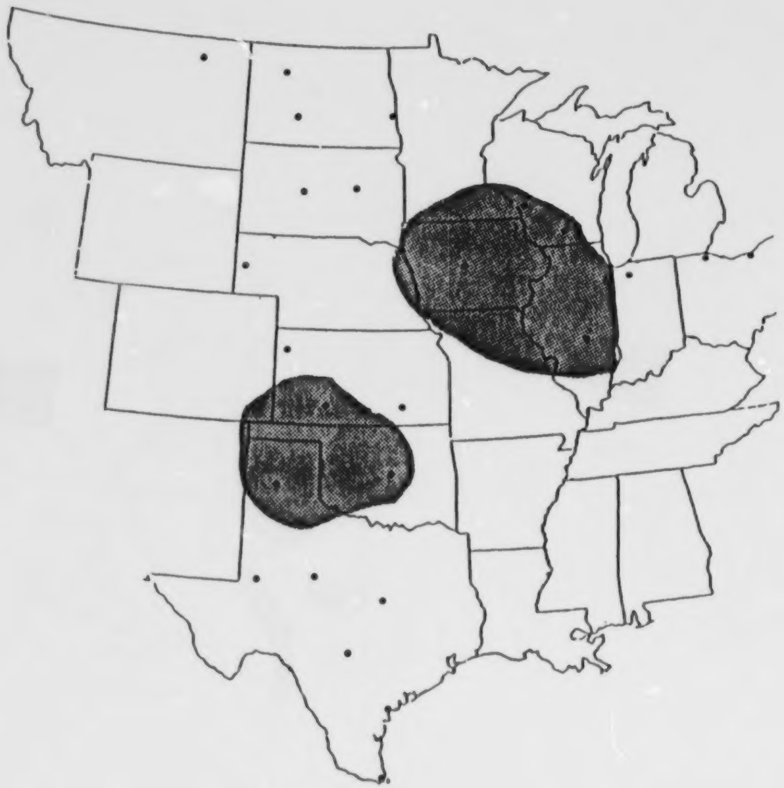

Figure 5a. PRZM modeled areas of maximum potential 30-year median annual subsurface leaching for highly soluble/short-lived and slightly soluble/long-lived pesticides under historical (base) weather conditions (leaching > 100 mg/ha/yr).

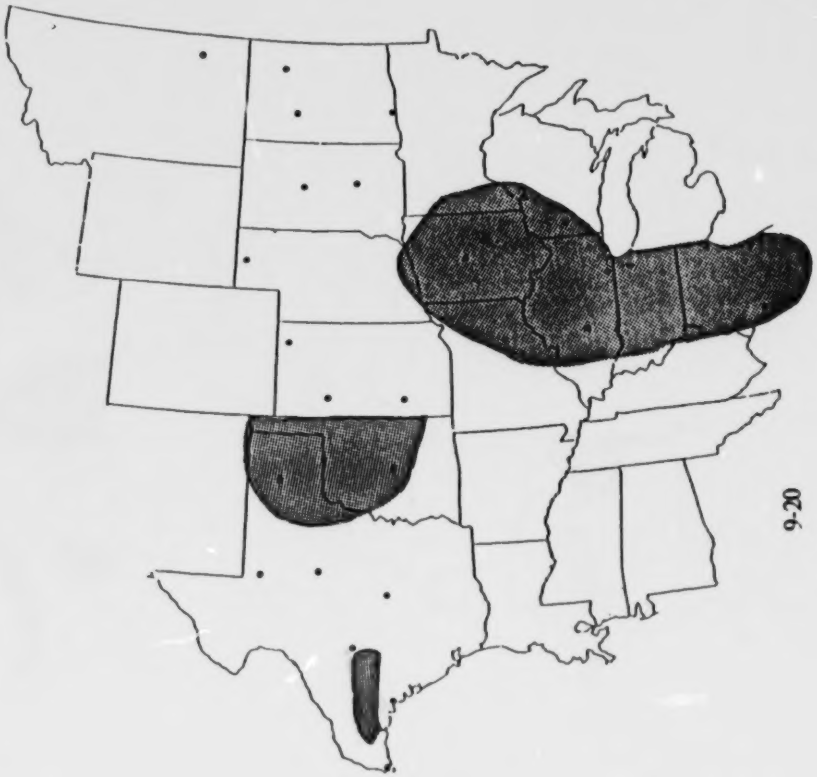

Figure 5b. PRZM modeled areas of maximum potential 30-year median annual subsurface leaching for highly soluble/long-lived pesticides under historical (base) weather conditions (leaching > 20,000 mg/ha/yr).

Table 5. Comparison of experimental and PRZM simulated surface pesticide losses.

	Chemical	Location	Soil Texture	Cover Crop	Length of Experiment	Application Rate kg/ha	Concentration Estimated (μg/liter)	Reference
Experiment	Metribuzin	Stoneville, MS	Sandy loam	Soybeans	1-5 months	.56	10-53	Wauchope, et al. (1977)
PRZM - BASE	Highly Soluble Short-Lived	Corpus Christi, TX	Sandy loam	Cotton	30 years	1.12	2-1529	
- GISS					30 years		32-1436	
- GFDL					30 years		2-1485	
Experiment	Atrazine	Coshocton, OH	NA	Corn	3 months	1.12	180	Edwards (1972)
PRZM - BASE	Highly Soluble Long-Lived	Cleveland, OH	Sandy loam	Corn	30 years	1.12	221-973	
- GISS					30 years		355-1017	
- GFDL					30 years		317-1018	
Experiment	Trifluralin	Lewisberg, NC	Sandy loam	Cotton	6-7 months	1.12	7-24	Sheets, et al. (1972)
PRZM - BASE	Slightly Soluble Long-Lived	Corpus Christi, TX	Sandy loam	Cotton	30 years	1.12	158-488	
- GISS					30 years		299-475	
- GFDL					30 years		191-474	

The mass of slightly soluble/long-lived or highly soluble/short-lived pesticide leached is compared to that which was initially applied in Table 6. Table 6 indicates that the median percent of applied highly soluble/short-lived pesticide lost per year under base conditions ranges from .02% to 2.0%. Under the GISS climate scenario, the range is unchanged. Under the GFDL scenario, the range decreases dramatically. The median percent of less soluble/long-lived pesticide lost per year under base conditions ranges from .03% to 3.9%. Neither climate change scenario results in significant change in the mass of this pesticide lost per year. The values in Table 6 represent the mass of pesticide moving out of the bottom of the crop root zone. No downward transport beyond the root zone is included in the present study, so no statement can be made concerning when (rate of movement) or if (degradation rate) these leached pesticides will actually reach an aquifer. Areas which the model indicates experience the greatest leaching of highly soluble/short-lived and slightly soluble/long-lived pesticides on sandy soils under base conditions include the Texas Panhandle, Oklahoma, southwestern Kansas, Iowa, Illinois, and Wisconsin.

Figure 5b illustrates maximum leaching areas for highly soluble/long-lived pesticides. The areas of maximum model estimated leaching are the same as for highly soluble/short-lived and slightly soluble/long-lived pesticides, but also include portions of the Texas Blacklands and Ohio. Mean annual losses of highly soluble/long-lived pesticide under base weather conditions range from 2.0×10^4 mg/ha/yr to 3.0×10^5 mg/ha/yr. Table 6 indicates that this represents an annual loss of 3.32% to 27% of the initial pesticide application. Both GISS and GFDL climate change scenarios lead to a downward shift of the range of mass losses, but the significance of the shift is undetermined. The results presented in Figures 5a-b and Table 6 represent worst case scenarios and do not necessarily reflect the mixture of erodable and non-erodable soils used in current agricultural production.

SURFACE WATER IMPLICATIONS

If the consensus results of Table 3 are applied to Figures 4a-c, the implications are that those areas the model indicates to be most likely to experience surface pesticide load problems under current weather conditions in the spring wheat and corn regions could improve (decrease) under the CO_2 doubling. Although chemical load may decline, it does not necessarily follow that concentrations will decline. Table 5 summarizes base and climate change maximum concentration events at selected locations. The same procedure used to determine the statistical significance of changes in chemical loadings was applied to the concentration distributions. Results indicate that at the two specific locations presented in Table 5, there is no significant change in the distribution of maximum concentration events. Thus, even though the chemical runoff load increases significantly under the GFDL scenario across the corn region, the concentration of the chemical entering an adjacent water body from a point within the region may not necessarily increase as well.

If a pesticide is removed from a field primarily in the sediment phase of runoff, then its loss might be controlled by standard soil conservation practices. Unfortunately, many of today's pesticides are lost mainly in the water phase (Wauchope, 1978; EPA, 1984; Maas et al., 1985). Erosion control practices, unless they control water as well as sediment losses, can be expected to have little effect on runoff losses of pesticides, except those having solubilities of 1 ppm or less (Wauchope, 1978; Maas et al., 1985). This implies that soil conservation technology that emphasizes sediment control could help to offset the surface loss increases indicated by PRZM for slightly soluble/long-lived pesticides (solubility = .05 ppm). Such measures are not expected to help surface losses of highly soluble/short-lived pesticides (solubility = 1,220 ppm) or highly soluble/long-lived pesticides (solubility = 33 ppm), unless runoff control measures are also implemented.

GROUNDWATER IMPLICATIONS

The consensus results of Table 3 may be applied to Figures 5a and b to assess the implications to groundwater. Leaching of pesticides below the crop root zone should decrease everywhere except perhaps on silty soils in the cotton region. This overall decline, as discussed earlier, most likely is a result of higher evaporative demands and increased runoff volumes, resulting in less moisture available for infiltration and deep

Table 6. Median Annual Leaching Losses Through Sandy Loam Soils in the Maximum Loss Areas of Figures 5a and b Expressed as a Percent of Annual Pesticide Application (1.12 kg/ha)

PESTICIDE	BASE	SCENARIO GISS	GFDL
Highly Soluble Short-Lived	.02% to 2.00%	.01% to 2.9%	.01% to .77%
Highly Soluble Long-Lived	3.32% to 27.00%	.02% to 21.60%	.02% to 23.90%
Less Soluble Long-Lived	.03% to 3.90%	.02% to 3.10%	.10% to 3.00%

percolation. However, as in the case of surface losses, decreased loads do not necessarily imply decreased concentrations of pesticide transported beyond the root zone.

From a water quality perspective, decreased pesticide leaching may be advantageous. From a water quantity perspective, these results could be cause for concern. Less leaching can imply less water moving through soil profiles and less water available for aquifer recharge. If water demands were to increase at the same time there was a decrease in the recharge rate, competition for scarce water resources would increase dramatically.

A second implication, particularly for rapidly recharging aquifers, arises from the management response to increased surface pesticide losses suggested earlier. Runoff reducing conservation practices will generally reduce surface pesticide loadings more than surface concentrations. While such practices may increase infiltration, more pesticide also could remain to be transported downward and pesticide concentrations in infiltration water could increase (Maas et al., 1985). Situations could arise in which decisions concerning which resource to protect, surface or groundwater would be required. Given the PRZM chemical load estimates and recent estimates of county-scale groundwater vulnerability (Alexander et al., 1986), those study areas most likely to be facing such decisions are the Cotton and Winter Wheat cropping regions.

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APPENDIX A

THE STATISTICAL NATURE OF PRZM ESTIMATED MODEL OUTPUT AND IMPLICATIONS FOR CLIMATE CHANGE SCENARIO INTERPRETATION

The skewed nature of the chemical transport results presents some problems for even a simple descriptive statistical summary. In response, the central tendency of a sample is presented in terms of the median rather than mean. Climate change impacts are presented in terms of percentage change from the base case median to the GISS or GFDL medians.

Since variability in the model output is about 2 to 3 orders of magnitude greater than the median, it is prudent to consider the statistical significance of the model indicated climate change impacts. The extreme non-normality of the sample does not lend itself to standard parametric tests which often assume Gaussian distributions. A two-sample t-test applied to the sample ranks is equivalent to a Mann-Whitney-U using the t approximation for the significance level (SAS, 1982). The two sided null hypothesis is, H_0: the populations have identical distributions and H_1: the populations differ with respect to location. Impact results contained in the regional analysis that are significant at the .90 level are denoted by * in the tables of this report. Those results significant at the .95 level are denoted by **.

For an example of further statistical considerations connected with PRZM model output, consider the climate change impact results contained in Table 8, Appendix B (Regional Analysis). The absolute values of the changes contained in Table 8 vary greatly. Note also the rarity of statistically significant results (none for the GISS scenario and five cases for GFDL). Both of these observations arise from the large variability in the model results. Even though some regional model changes are very large, sample variability is much larger, resulting in an inability to reject the null hypothesis of identical distributions.

As sample size increases among homogeneous observations, variance usually decreases and the sample distribution approaches the normal distribution (central limit theorem). In the case of regional climate change results, this does not occur. The variance of the distribution of annual PRZM estimated chemical transport does not decrease as more sites and scenarios are added to a region. This suggests that there is significant variability among locations and scenarios within the region. That is, climatologically and physically the stations are not homogeneous.

Another factor which influences the variability of the results is the use of multiple climate change grid boxes within a single crop region. The direction and magnitude of modeled climate change is rarely consistent across grid box or climate scenario. This serves to alter the existing time-space autocorrelation patterns among stations within the cropping region. There is every indication that natural spatial variability across climate, soil, tillage, and pesticide within a region, can be greater than the climate change whose impact is to be assessed (Eddy and Sladewski, 1988). Large percentage changes and consensus results may be obtained, but the changes infrequently attain statistical significance. Some of these regional "signal" versus "noise" biases might be decreased by appropriate data stratification prior to significance testing.

APPENDIX B

REGIONAL CLIMATE CHANGE RESULTS AND INTERPRETATION

The Northern Great Plains (Spring Wheat)

Table 7 contains mean monthly GCM estimated temperature and precipitation modifications across the spring wheat region. Table 8 contains a summary of resultant pesticide transport changes for this cropping area. The values in Table 8 were obtained by determining the 30 year mean parameter value for across 81 scenarios at each weather site within the region. For spring wheat this is a sample of 486 30-year means. The regional transport values in Table 8 represent comparisons of the median of the base 486 scenario means with the median of each set of 486 GCM scenario means. The 3 sets of means were then stratified by soil or pesticide and the same comparison of medians performed, this time with samples of 162 scenario means. Table 7 can be used to suggest possible sources of the changes noted in Table 8. For instance, when all management scenarios are considered together, there is an overall decrease in pesticide runoff transport under the GFDL scenario. The GFDL scenario contains an increase in planting time precipitation, which could then generate an increase in runoff and erosion of highly soluble/short-lived pesticides. Decreased runoff and erosion of longer lived chemicals reflects GFDL precipitation decreases for the remainder of the growing season. Leaching of active chemical below the root zone is decreased throughout. This is the result of a smaller volume of water available to move chemicals through the profile or less pesticide remaining on the surface for downward transport.

The Central Plains (Winter Wheat)

Table 9 contains a summary of regional climate change impacts for the Central Plains. GISS runoff results and regional erosion show high statistical significance. That is, the alternative hypothesis of a shift in the distribution of pesticide transport cannot be rejected. The smallest change under the GISS scenario is noted on clay soil with slightly soluble/long-lived pesticides. The largest increases under the GISS scenario are found when the entire population of scenarios in the region are considered with highly soluble/short-lived and slightly soluble/long-lived pesticide subgroups. GFDL runoff results are mixed. Greatest chemical runoff increases are noted among the highly soluble/long-lived pesticides. Greatest chemical runoff declines are noted on sandy soils.

Table 10 contains the mean monthly GISS and GFDL model-produced regional precipitation and temperature changes across the winter wheat cropping region. Under both climate scenarios, relatively dry plant and preplant conditions exist, but the remainder of the growing season (October through May) shows increased precipitation. Monthly precipitation changes across the two climate scenarios are consistent except during August. There is no crop in the field at this time, and surface losses of remaining pesticides will be at their greatest. Table 10 suggests that GISS planting conditions are more moist. If so, there is less soil infiltration because the profile is already full and more pesticide is available to be washed-off when the rains return. Dry August conditions under the GFDL climate change scenario encourage greater soil infiltration when water is available leaving less chemical on the surface for later removal. Subsurface leaching of pesticide is less under GFDL than GISS. This is the result of greater GFDL summertime temperature increases. As in the Northern Plains, less moisture is left for later downward transport of chemicals.

Table 7. 30-Year Mean Monthly Precipitation and Temperature Changes For the Spring Wheat Cropping Region Under GISS and GFDL Climate Change Scenarios

MONTH	PRECIPITATION (% CHANGE FROM BASE)		TEMPERATURE (°C CHANGE FROM BASE)	
	GISS	GFDL	GISS	GFDL
Jan	-18	+19	+6.16	+4.47
Feb	+30	+30	+5.71	+5.97
Mar	-12	+27	+5.51	+6.03
Apr (P)*	-8	+20	+4.85	+5.38
May	-3	-13	+3.50	+4.01
Jun	-12	-28	+3.59	+8.73
Jly	-17	-16	+3.38	+8.62
Aug (H)*	+35	-17	+3.88	+7.95
Sep	+104	-10	+5.43	+6.54
Oct	-2	-10	+4.49	+5.57
Nov	-26	+31	+3.82	+6.25
Dec	+5	+1	+5.47	+6.19

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* (P) = Crop planted
  (H) = Crop harvested

Table 8. GISS and GFDL Scenario Impacts on Median Values of Pesticide Transport in the Spring Wheat Cropping Region

	GISS IMPACT (% CHANGE FROM BASE)	GFDL IMPACT (% CHANGE FROM BASE)
Surface Runoff:		
Region (all scenarios)	+6	-11
Highly Soluble/Short-Lived	+2	+45**
Highly Soluble/Long-Lived	+4	-21
Slightly Soluble/Long-Lived	+5	-25**
Clay	+8	-2
Sand	+4	-7
Silt	+9	0
Surface Erosion:		
Region (all scenarios)	+17	+17
Highly Soluble/Short-Lived	+41	+126**
Highly Soluble/Long-Lived	+1	+5
Slightly Soluble/Long-Lived	+10	-9
Clay	+10	0
Sand	+25	+50
Silt	+19	+7
Subsurface Leaching:		
Region (all scenarios)	-23	-63
Highly Soluble/Short-Lived	-41	-53
Highly Soluble/Long-Lived	-22	-69**
Slightly Soluble/Long-Lived	-46	-84**
Clay	-22	-41
Sand	+71	-19
Silt	-10	-11

* Result significant at the .90 level
** Result significant at the .95 level

Table 9. GISS and GFDL Scenario Impacts on Median Values of Pesticide Transport in the Winter Wheat Cropping Region

	GISS IMPACT (% CHANGE FROM BASE)	GFDL IMPACT (% CHANGE FROM BASE)
Surface Runoff:		
Region (all scenarios)	+100**	-5
Highly Soluble/Short-Lived	+74	+1
Highly Soluble/Long-Lived	+96**	-16
Slightly Soluble/Long-Lived	+69**	-8
Clay	+168**	-1
Sand	+104*	+19
Silt	+73**	-5
Surface Erosion:		
Region (all scenarios)	+49*	-13
Highly Soluble/Short-Lived	+42	-16
Highly Soluble/Long-Lived	+65	+12
Slightly Soluble/Long-Lived	+47	-19
Clay	+63	+15
Sand	+34	-3
Silt	+43	-7
Subsurface Leaching:		
Region (all scenarios)	-6	-36
Highly Soluble/Short-Lived	+10	-43
Highly Soluble/Long-Lived	+10	-32
Slightly Soluble/Long-Lived	+29	-15
Clay	+127	+7
Sand	-28	-43
Silt	-32	-65

* Result significant at the .90 level
** Result significant at the .95 level

Table 10. 30-Year Mean Monthly Precipitation and Temperature Changes For the Winter Wheat Cropping Region Under GISS and GFDL Climate Change Scenarios.

MONTH	PRECIPITATION (% CHANGE FROM BASE)		TEMPERATURE (°C CHANGE FROM BASE)	
	GISS	GFDL	GISS	GFDL
Jan	+12.0	+38.4	+5.54	+4.13
Feb	+12.3	+28.2	+4.44	+5.30
Mar	+32.4	+10.1	+5.53	+4.61
Apr	+8.7	+37.0	+4.85	+4.81
May	+13.4	+7.3	+3.11	+5.84
Jun (H)*	-.4	-44.4	+3.39	+5.87
Jly	-.8	-40.0	+4.20	+6.23
Aug	+18.2	-32.0	+4.65	+4.57
Sep	-14.5	-17.0	+4.19	+4.79
Oct (P)*	-15.2	-18.9	+5.66	+4.89
Nov	+20.0	+49.1	+5.52	+4.65
Dec	+10.5	+18.6	+5.67	+5.39

* (P) = Crop planted
(H) = Crop harvested

The Southern High Plains and Blacklands (Cotton)

Table 11 contains the regional double CO_2 impacts computed from PRZM model results for the Southernigh Plains and Blacklands areas. Statistically significant GISS impacts include: a regional chemical runoff increase; an increase in highly soluble/short-lived and slightly soluble/long-lived pesticide runoff; and an increase in highly soluble/short-lived surface pesticide erosion. The only statistically significant GFDL result is an increase in slightly soluble/long-lived pesticide surface erosion. In general, GISS and GFDL impact results suggest increased surface pesticide runoff and erosion across all pesticides and all soils. Subsurface leaching decreased across most pesticides and soils.

Table 12 which contains monthly GISS and GFDL precipitation and temperature changes, provides a source for such impacts. As in the case for winter wheat, both GISS and GFDL scenarios indicate precipitation declines during the time of year when the fields have the least ground cover (October-February). In February, there is a GISS precipitation increase. Some increase of GISS surface erosion and runoff could be noted here. Planting conditions would be more moist and, since the soil profile is filled, more surface runoff would result than in the drier GFDL case. Leaching in both scenarios generally decreases because of increased surface losses and decreased excess moisture capable of carrying pesticides out the bottom of the root zone.

Central Prairie (Corn)

Table 13 contains regional $2XCO_2$ induced pesticide transport changes across the corn cropping area. No GISS change scenario results were statistically significant. Significant GFDL results include: a decrease in regional surface runoff; a decrease in highly soluble/long-lived surface runoff; and a decrease in regional subsurface leaching and highly soluble/short-lived leaching. Most GISS and GFDL results for surface and subsurface transport appear to agree that the GCM estimated climate change would result in decreases in chemical losses in the Central Prairie.

Precipitation increases under the climate change scenarios occur primarily during December, January, and February when sub-freezing temperatures would likely result in the moisture being stored as snowpack (Table 14). If the snowpack melts slowly when warm spring temperatures arrive, the impact of increased wintertime precipitation on chemical runoff and erosion is minimized. The majority of the moisture would serve to recharge soil moisture. If the snow melts rapidly over a frozen subsoil, erosion would be substantially higher. Summertime temperatures increase for both climate change scenarios, most dramatically in the GFDL scenario, increasing soil moisture demands. Increases in plant and evaporative demand resulting from these much higher temperatures exceed modest early season precipitation gains. Late season precipitation declines exacerbate the situation. The result is that more soil water is needed to support plant and evaporative demands and less is available for pesticide transport out of the root zone. More pesticide is stranded within the profile to degrade into non-reactive chemical constituents.

Table 11. GISS and GFDL Scenario Impacts on Median Values of Pesticide Transport in the Cotton Cropping Region

	GISS IMPACT (% CHANGE FROM BASE)	GFDL IMPACT (% CHANGE FROM BASE)
Surface Runoff:		
Region (all scenarios)	+23**	+17
Highly Soluble/Short-Lived	+50**	+11
Highly Soluble/Long-Lived	+14	+36
Slightly Soluble/Long-Lived	+13*	+46**
Clay	+18	+16
Sand	+26	+11
Silt	+19	0
Surface Erosion:		
Region (all scenarios)	+35	+8
Highly Soluble/Short-Lived	+37*	-21
Highly Soluble/Long-Lived	+22	+1
Slightly Soluble/Long-Lived	+17	+18
Clay	+25	+12
Sand	+53	-12
Silt	+31	+15
Subsurface Leaching:		
Region (all scenarios)	0	-35
Highly Soluble/Short-Lived	+97	+29
Highly Soluble/Long-Lived	-40	-51
Slightly Soluble/Long-Lived	-31	-52
Clay	-33	-66
Sand	-34	+150
Silt	+5	+14

* Result significant at the .90 level
** Result significant at the .95 level

Table 12. 30-Year Mean Monthly Precipitation and Temperature Changes For the Cotton Cropping Region Under GISS and GFDL Climate Change Scenarios

MONTH	PRECIPITATION (% CHANGE FROM BASE)		TEMPERATURE (°C CHANGE FROM BASE)	
	GISS	GFDL	GISS	GFDL
Jan	-33.3	-12.5	+4.69	+3.65
Feb	+3.8	-1.6	+3.87	+4.85
Mar	-27.2	+35.9	+4.82	+4.46
Apr (P)*	-1.2	-14.9	+4.69	+3.87
May	+22.2	-29.1	+2.87	+5.90
Jun	-19.8	+103.7	+4.23	+3.37
Jly	-6.1	-2.3	+4.26	+4.29
Aug	+12.1	+82.4	+4.73	+3.55
Sep	+53.7	-25.4	+3.29	+4.35
Oct (H)*	-16.2	+5.1	+5.29	+4.72
Nov	-39.9	+17.8	+5.27	+4.38
Dec	-4.8	-12.3	+5.91	+4.85

* (P) = Crop planted
(H) = Crop harvested

Table 13. GISS and GFDL Scenario Impacts on Median Values of Pesticide Transport in the Corn Cropping Region

	GISS IMPACT (% CHANGE FROM BASE)	GFDL IMPACT (% CHANGE FROM BASE)
Surface Runoff:		
Region (all scenarios)	+1	-28**
Highly Soluble/Short-Lived	-12	-15
Highly Soluble/Long-Lived	0	-31**
Slightly Soluble/Long-Lived	0	-32
Clay	+10	-24
Sand	0	-30
Silt	+3	-27
Surface Erosion:		
Region (all scenarios)	-4	-12
Highly Soluble/Short-Lived	-12	-7
Highly Soluble/Long-Lived	-5	-13
Slightly Soluble/Long-Lived	-5	-20
Clay	0	-5
Sand	+3	-8
Silt	-4	-2
Subsurface Leaching:		
Region (all scenarios)	-30	-87*
Highly Soluble/Short-Lived	-23	-82*
Highly Soluble/Long-Lived	-28	-24
Slightly Soluble/Long-Lived	-66	-57
Clay	-61	-69
Sand	-15	-54
Silt	-21	-88

* Result significant at the .90 level
** Result significant at the .95 level

Table 14. 30-Year Mean Monthly Precipitation and Temperature Changes For the Corn Cropping Region Under GISS and GFDL Climate Change Scenarios

MONTH	PRECIPITATION (% CHANGE FROM BASE)		TEMPERATURE (°C CHANGE FROM BASE)	
	GISS	GFDL	GISS	GFDL
Jan	+11.9	+35.3	+6.25	+5.35
Feb	+6.3	+30.1	+5.17	+4.43
Mar	+17.7	+10.0	+5.11	+5.15
Apr	+4.8	+1.9	+5.10	+4.87
May (P)*	+8.9	+8.9	+2.92	+3.79
Jun	+5.0	-25.2	+3.67	+7.51
Jly	+12.7	-29.0	+2.71	+7.78
Aug	-2.1	+8.8	+3.92	+5.07
Sep	-33.9	-29.0	+6.55	+6.58
Oct (H)*	-12.5	+6.5	+3.87	+5.55
Nov	-14.1	+14.5	+5.71	+5.51
Dec	+16.4	+36.6	+6.05	+6.34

* (P) = Crop planted
(H) = Crop harvested

FARM-LEVEL ADJUSTMENTS BY ILLINOIS CORN PRODUCERS TO CLIMATIC CHANGE

by

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FINDINGS[1]

Adjustments to existing production practices are the first line of defense against climate change. Production practices currently in use by corn producers can be altered with little cost to the farmer in order to cope with some types of climatic fluctuation. Examples of such adjustments include altering planting dates, crop mixes, tillage practices, and fertilizer applications (these are elaborated on below). This analysis suggests the possibility that, in some scenarios of climate change, such adjustments could totally eliminate negative climate impacts or even create a positive growth situation. The net effect of climate change on corn production after adjustments are made by farmers will be significantly different from the effect of climate change without adjustments.

More severe climatic changes are likely to make major adaptations necessary. If climatic conditions were to become as hot and dry during the summer growing season in Illinois as is projected by the GFDL model, then farmers who are used to raising full-season corn will be forced to adopt production practices that are quite different from those in use today. Such adaptations would be necessary to deal with the potentially high heat and moisture stress conditions that are likely to accompany such climatic changes. Examples of adaptations that are likely to be made include installation and use of irrigation systems; changes in crop mix to include some combination of short-season corn, soybeans and grain sorghum; and removal of some marginal land from production on a given farm.

Climate changes in nongrowing season parts of the year will be important, and nongrowing season adjustments are likely to follow. Climate change will occur in all seasons. Indeed, in the Northern Hemisphere mid-latitudes, changes may be most dramatic in winter. Climate changes in the nongrowing season (fall postharvest and winter) will affect some adjustment decisions. For example, a warmer and wetter winter would increase nitrogen leaching and denitrification thus leading to a likely reduction of pregrowing season fall-applied fertilizer.

Changes in regional comparative advantage will determine the extent of adjustment versus adaptation. The effect of climate on agricultural regions competing with Illinois will directly influence how adjustments and adaptations are made by Illinois producers. Economics apart, neither the GFDL nor the GISS 2xCO_2 climate scenarios would preclude corn from being raised in Illinois if appropriate adjustments (e.g., earlier planting, altered tillage) and adaptations (e.g., irrigation, short season varieties) are made. However, when economics come into play, many of these adjustments may raise production costs high enough to make corn production unprofitable relative to other regions or other crops. On the one hand, if other production regions are similarly adversely affected by the climate change and world demand for food and fiber cannot be met, then market prices could rise. Such price increases would encourage more extensive efforts to adjust and adapt production to the climate change. On the other hand, if comparative advantages begin to weigh more heavily in favor of other regions as climate changes, prices do not go up and necessary adjustments by Illinois farmers become too costly, the only strategy left for Illinois farmers is to leave farming altogether or, more likely, to choose a new crop to grow.

If prices for crops uniformly rise, as predicted by Adams (this volume), and input prices do not rise significantly, then adjustments are likely to be extensive in Illinois. I consider what sorts of specific adjustments and adaptations that might be in store in the following two sections.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Contract No. CR-814653-01-0, it does not necessarily reflect the Agency's vieews, and no official endorsement should be inferred from it.

Specific Adjustment Possibilities

A number of adjustments to existing production practices could be made by Illinois corn producers in response to changes in climate:

1. Changes in tillage practices. This research points to increased fall conservation tillage in Illinois. This would offset the negative effects of a smaller possible number of field days in the following spring planting season and would take advantage of dry conditions in the fall season. Though this response may not, by itself, have a large effect on yields, it will contribute in a significant way to how farmers may respond.

2. Less fall-applied nitrogen. Questions aside about the continued production of corn in Illinois under climate change, less nitrogen is likely to be applied in fall. If nitrogen-fixing legumes such as soybeans replace corn in Illinois, then less nitrogen use needs no explanation. However, if corn and other crops which benefit from nitrogen application continue to be grown then the explanation for less fall-applied nitrogen is the desire to avoid leaching and denitrification during the warmer (and possibly wetter) winter.

3. Planting earlier in the spring. It will benefit farmers to plant corn earlier in the spring than at present. Earlier planting will result in the occurrence of anthesis (a period of high temperature and moisture stress sensitivity) earlier in the summer when temperatures and soil moisture levels are less likely to be at stress levels. Earlier planting could be enhanced by warmer spring temperatures. However, the warmer spring temperatures could be offset somewhat by the greater heat storage capacity of a wetter soil (wetter from higher than current precipitation in winter), i.e., as soil moisture increases, more energy is needed to raise the temperature of the soil.

4. Changes in corn varieties. Climatic change will encourage farmers to alter the corn varieties planted either to maximize potentially beneficial climate changes or to minimize potentially negative climate changes. If planted earlier than present, there is a possibility that high yielding, full season varieties would do well under the GISS $2xCO_2$ summer climate. Also, if planted earlier than now, low yielding short-season corn varieties could be grown under the relatively harsh GFDL $2xCO_2$ summer climate.

5. Lower planting densities. Potentially drier soils during summer will likely lead to changes in planting densities. Lowering the number of plants per unit area would conserve soil moisture. Given that planting densities have been increasing steadily in recent years, it is likely that densities will be higher than present but not as high as they would have been without climate change.

6. More attention to pests. Warmer temperatures are likely to stimulate greater pest problems (this is handled more extensively by Skinner et al., this volume). It would be reasonable to expect farmers to respond with some increase in pesticide use but perhaps accompanied by greater emphasis on integrated pest management practices.

7. Earlier harvest. If planting does occur earlier in the spring than now, it follows that harvest will begin earlier than now. This is especially true if short-season varieties were planted in spring. Also, changes toward warmer and drier late summers and early falls are likely to favor earlier corn maturation and to accelerate drydown. Not only would farmers be able to harvest earlier than now, but there is likely to be less need for artificial drying.

Specific Adaptation Possibilities

1. Altered crop mixes. Depending upon the exact nature of climatic change, farmers are likely to change not only the varieties of corn to be raised, but also to alter the types of crops grown. Crop mixes could become more diverse with likely combinations (either intercropped or annually rotated) of corn, soybeans, and grain sorghum. If corn is grown under the GFDL $2xCO_2$ scenario, then almost certainly it will be a short-season variety.

2. Increased irrigation. According to the experts, current climatic and economic conditions would support use of irrigation in Illinois approximately 3 years out of 10 years. Climatic changes, especially changes which leave

soils drier during summer than now, will likely lead to increased use of irrigation in Illinois. Increased use of irrigation is supported by projected price increases for all crops likely to be grown in Illinois. However, not all farmers can be expected to turn to irrigation as climate changes. Insufficient water supply and nonirrigable soils will limit where irrigation may come into practice. Moreover, even with severe climatic changes, some crops may be profitably grown without irrigation (e.g., soybeans, grain sorghum).

3. Marginal land taken out of production. If climatic changes cause production costs to rise in Illinois, there is likely to be a corresponding decrease in total acreage planted on a given farm. Poorer quality land (less fertile, highly erosive) on any farm is likely to be taken out of production. Such action would tend to help hold the line on reductions of productivity per unit of land.

CHAPTER 1

INTRODUCTION

Background

Scientific consensus is emerging that climatic change will impact production agriculture (Rosenberg, 1986; Ciborowski and Abrahamson, 1986). The extent of impacts is not clear nor is it known, on balance, whether impacts will be positive or negative. This uncertainty stems partly from incomplete knowledge of how climate will change and partly from lack of understanding of how agricultural systems will adjust to impacts of changing climate.

The purpose of this paper is to provide insight on how existing farm level production technologies might be adjusted in response to dynamic climate. The focus will be on corn production in Illinois as representative of production agriculture in the core of the midwestern Grain Belt.

Why corn production and why Illinois? Corn was second only to soybeans over the period 1978-1982 in share of total U.S. agricultural output held by major grains (corn, wheat, soybeans, grain sorghum). It is a major agricultural export commodity, again second only to soybeans among grains and it is, thus, a major international trade commodity in the overall U.S. export economy.

Illinois (17%) is second only to Iowa (21%) in percentage of U.S. corn produced. Approximately 81% of the total land area of Illinois comes under the plow. Much of this 81% is cultivated with corn. Moreover, in 1985, Illinois led all Corn Belt states in value per acre of land and buildings.

Corn, regardless of where it is grown, is sensitive to vagaries of climate and weather. Perhaps more than any other major grain crop, corn yields can be substantially reduced (or enhanced) by anomalous weather conditions. Recent Illinois droughts (e.g., 1976, 1980, 1983, 1988) have resulted in major documented corn yield disruptions across the state. Indeed, Richman and Easterling (in press) have shown that anomalous weather conditions strung out over several growing seasons can be detected in corn yield time series, account being taken for technology enhancements of yields.

Research Objectives

Specific objectives of the research reported here are the following:

1. To identify the climate sensitivities of current farm-level corn production technologies in Illinois, especially those which may be subject to adjustments under climate changes specified in NASA/GISS and GFDL GCM runs with doubled ambient carbon dioxide levels (henceforth $2xCO_2$).

2. To determine, under a set of constraining assumptions, decision options for adjusting production technologies to climate change.

3. To identify situations (e.g., applications of policy, economic conditions) that might facilitate or hinder certain adjustment decisions.

4. To develop a set of hypothetical scenarios in which farmers adjust to climate change.

5. To identify a set of environmental policy issues relating to farm level adjustments to climate change.

CHAPTER II

METHODOLOGY

Despite several decades of rapid technological advance in production agriculture, climate continues to exert strong influences on productivity (Warrick, 1984). Sensitivity and resiliency of agricultural systems have been suggested in recent empirical analyses. These studies not only document climate impacts on production, but also the capacity of agriculture to adjust and adapt to climate. For example, Parry et al. (1986) have coordinated a series of studies showing that crop production at various growing margins (e.g., cold, warm/dry) around the world are responsive to small shifts in climate. Rosenberg (1982) demonstrated that hard red winter wheat production has expanded geographically in the North American Great Plains across spatial climatic gradients that exceed predicted climatic changes from the greenhouse effect. Adaptability of wheat culture was inferred from this expansion.

While useful insight is gained from empirical hindsight studies such as those cited above, it is not entirely possible to base predictions of future agricultural response to climatic change on such analysis. New production technologies and occurrence of economic and social conditions unlike any of today will likely make agriculture quite different in the future. Yet, existing predictive studies have their own problems. Blasing and Solomon (1982) examined climatic constraints on corn production in light of a scenario of future climatic change leading to changes in temperature and precipitation. They concluded that the Corn Belt would shift on an axis from southwest to northeast in the United States (and into S. Canada). Moreover, they concluded that much of the Corn Belt that is now in dryland farming would be forced to rely on irrigation, and many currently irrigated Corn Belt locations would be forced out of corn production.

Rosenzweig (1985) used a similar approach to Blasing and Solomon. She used a general circulation model (GCM)-based projection of climatic change, under CO_2 doubling, to examine wheat production in the United States. In general, potential wheat producing areas were found to expand under climatic change. Some cultivars would likely be stressed by high temperatures along the current southern boundary of wheat production.

Though studies such as these provide useful first approximations of how climate might affect production, they do have deficiencies. First, they tend to rely on a single scenario of climatic change. Rosenberg (1987) has demonstrated major differences between sophisticated GCM predictions of climate change for important agricultural regions such as the U.S. Midwest. He concludes it is best to consider a range of possible climate change scenarios in any attempt to estimate its impacts.

Second, these models do not explicitly consider potential incremental adjustments by farmers and related agribusiness. Yet, adjustments to production practices in response to climate change will play a major role in determining actual impacts on agricultural productivity. These adjustments must be considered before an accurate assessment of impacts can be made. Although Decker et al. (1986) cataloged a variety of agricultural impacts from CO_2-induced climatic change and possible adjustment strategies to climatic stress, little analysis was provided of conditions under which these adjustments might be made.

Third, in these analyses, agricultural impacts of climate change are examined in isolation from other less directly climate-linked trends in production agriculture. In essence, the future economic context of agriculture is ignored. Therefore, these studies, like empirical hindsight studies, must be viewed with caution in making projections about the future. Some foreseeable trends such as more restrictive use of pesticides on the farm may conflict with logical strategies for coping with pest outbreaks brought about in part by changing climate. These trends make it important that agricultural impact studies be cast within a broader context of climate and nonclimate influences on production.

Focus on Farm-level Decision Making

In this study I focus on farm level decision making as the key to the understanding of how farmers might adjust existing technologies in response to climate change. I presume that decisions by a farmer on how to manage a crop are influenced by factors which affect productivity and hence profits. These factors include his knowledge of existing conditions and his rational expectations of near future conditions (Sonka and Lamb, 1987). Figure 1 shows knowledge and expectations of current and near future economic conditions such as, for example, market prices for inputs and outputs; environmental conditions such as, for example, soils, water quality and climate; and social values such as, for example, maintaining cultural traditions. Some of these conditions weigh more heavily than others in influencing a farmer's decision strategy. But they all must be examined if one is to try to understand how a farmer might behave in a particular way in managing a crop.

In this study my focus is on those production decisions by farmers which are influenced directly or indirectly by climate conditions. A number of techniques have been suggested for gaining insight into how production decisions might be influenced by climate. Lovell and Smith (1985) identify several microeconomic modeling approaches as being appropriate for this task including microsimulation, econometric, systems analysis, and input-output modeling. Decision analysis (Ausubel, 1980; Sonka and Lamb, 1987), in which some index of farmer well being is examined in light of various combinations of production decisions, is another possible approach. However, these approaches are somewhat time-consuming to develop and data-intensive and thus inappropriate for the task at hand.

The approach I chose for this study was to marshal expert judgment as to how farmers might adjust existing technologies to climate change. Specifically, I used what social scientists refer to as a case-scenario approach, which was modified with the inclusion of principles of the development of expert systems.

Case-scenario approaches involve the presentation of scenarios to individuals and then asking them how they might respond to any of the scenarios if they occurred. This is an accepted methodology for climate impact assessment (Wilhite and Easterling, 1987). The objective of this is to allow individuals to draw on their accumulated expertise in resolving a hypothetical problem. Glantz (1977) used this approach to ask decision makers what they might have done differently in response to a drought had they had available a perfect forecast of the drought beforehand. In the current study, experts were provided different scenarios of climate change and were asked how farmers-decision makers, given all of the climate and nonclimate factors that influence production decisions, might adjust existing technologies to cope with any problems the climate change might present. The justification for the use of the case-scenario approach and the manner in which the approach was carried out for this study will be amplified further below.

The procedure followed in this study to present climate scenarios to experts and to retrieve their assessments involved the use of expert system development principles.[2] I stress that this was not intended to lead up to the development of an expert system (at least not for this study) but rather was to provide a systematic framework for the gathering and synthesis of expert judgment. Put another way, the expert systems development principles are simply a means of adding rigor to the case-scenario approach.

Expert systems are developed using a process known as "knowledge engineering." Knowledge engineering is a structured interviewing process wherein modeler(s) and expert(s) interact to build a progression of expert logic beginning with basic assumptions, facts, and heuristics which lead to some solution or decision. In this research, the intent is to use knowledge engineering to assess factors influencing changes in farm production practices under climate change.

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[2] Expert systems are formally a branch of artificial intelligence. They are defined as computerized representations of human problem solving. All facts and heuristics ("rules-of-thumb") that an expert uses in a particular domain of expertise can be represented symbolically on a computer in such a form as to be used directly in resolving practical problems (Hayes-Roth, et al., 1983).

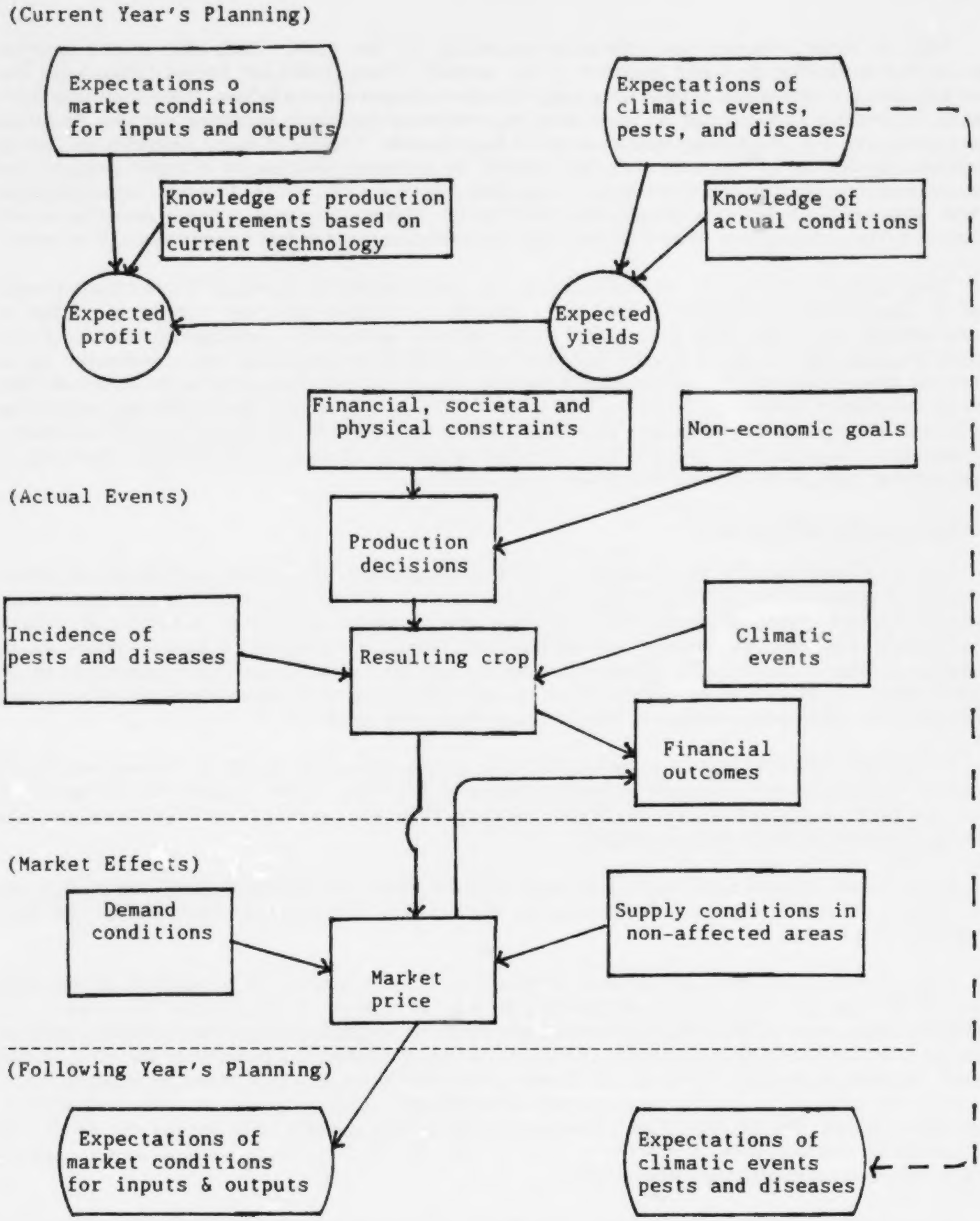
(Current Year's Planning)
Expectations o market conditions for inputs and outputs
Expectations of climatic events, pests, and diseases
Knowledge of production requirements based on current technology
Knowledge of actual conditions
Expected profit
Expected yields
Financial, societal and physical constraints
Non-economic goals
(Actual Events)
Production decisions
Incidence of pests and diseases
Resulting crop
Climatic events
Financial outcomes
(Market Effects)
Demand conditions
Market price
Supply conditions in non-affected areas
(Following Year's Planning)
Expectations of market conditions for inputs & outputs
Expectations of climatic events pests and diseases

Figure 1. Schematic of decision making at the farm level (after Sonka and Lamb, 1987).

Why use expert judgment and knowledge engineering for this study? Both offer several desirable characteristics in meeting the stated objectives of this research. Clark (1986) and Brewer (1986) argue that expert judgment is a valid means of developing insight into how complex systems behave. They imply that expert judgment is probably no better and no worse than large numerical models in predicting complex alternative futures, given data and methodology limitations of the large models. The use of expert judgment and the use of numerical models are not mutually exclusive. Indeed, the systematic combination of expert judgment and numerical modeling is a particularly strong form of analysis (Coulson, et al., 1987). However, expert judgment need not necessarily be linked to numerical models to be useful. This is particularly true when numerical models are limited by data scarcity, poor understanding of the processes being modeled, or a combination of these two.

Much practical expertise can be used to further the understanding of impacts of future climate change. There is considerable knowledge of how crops respond to weather and how farmers can adapt to weather-induced crop stress. This is supported by an extensive agroclimatic modeling and basic agronomic research literature and the accumulated expertise of county extension agents and crop consultants. But as pointed out above and elsewhere, such research is yet to be compiled and synthesized to useful models or other forms of information (Easterling and Sonka, submitted). It is proposed here that knowledge engineering provides a means of integrating undisputed factual information with less well documented heuristic information requiring expert judgment (e.g., interpretation of model output, use of nonscientific but valid knowledge in decisionmaking, assessment of reasonableness of future scenarios).

Knowledge Engineering Procedure

Two crop consultants (Dr. Harold Reetz, of the Potash and Phosphate Institute, and Mr. Ronald Olsen, of Top Soil, Inc.) with considerable knowledge of how climate affects Illinois corn production participated in the knowledge engineering (henceforth used interchangeably with knowledge acquisition). I intentionally avoided the inclusion of active farmers as experts. At this time most farmers are generally unaware of climate change implications for their own operations. However, I recognize that this is changing and future assessments should include farmers. The goal of the knowledge acquisition was to elicit from these experts ideas on likely responses by farmers to two alternative scenarios of climate change (discussed below).

Knowledge aquisition was structured to follow a simple conceptual model of climate and society interaction. Such models are discussed at length in Kates et al. (1985). Figure 2 shows that the process of climate and society interaction begins with climate changes. These are represented by GCM-based scenarios which are discussed further in the next section.

These climate changes result in physical impacts such as altered soil moisture, runoff, soil erosion, and so on. Climate changes directly cause physical impacts, which result in immediate agronomic impacts and likely prompt adjustments.

The knowledge acquisition procedure is based on the above schematic. It is repeated for individual seasons of the year (as these seasons are defined below). In addition to insight into how impacts and adjustments might occur within individual seasons, knowledge was sought as to how climate-altered conditions within one season might relate to agronomic conditions (including climate) in a previous or uncoming season. In many instances, a farmer's knowledge of climate-altered conditions in a past season or expectations of climate-altered conditions in an upcoming season may represent necessary contingencies for adjustment decisions in the current season. For example, if the farmer expects the upcoming winter to be warmer and wetter than now, then his fall (current) decision might be to apply less nitrogen (to avoid winter leaching) even though the now drier fall favors nitrogen application activities.

Another point raised in Figure 2 relates to the general economic, social, and political environment within which corn will be produced as climate changes. Nonclimate factors will undoubtedly influence how farmers will choose to respond to changing climatic conditions. Trends in technology, production costs, government programs, and markets, to name a few, will have some influence on how farmers will adjust to climate change.

Some of these nonclimate trends were identified in the knowledge aquisition procedure, and qualitative insight was sought as to their likely effect on climate adjustment decisions by farmers. Though I was unable to approach these nonclimate factors as systematically as I would have liked, any consideration of them at all breaks new ground in the climate impacts literature.

The experts were prepared for their interviews as follows:

1. They received a written statement of the research problem and the research objectives, including clear explanation of what was expected of them in knowledge engineering sessions.

2. They were shown scenarios of climate change produced by the GFDL $2xCO_2$, and the GISS $2xCO_2$ model runs (these are described below more fully).

3. They were shown projected yields for corn and soybeans based on the climate change scenarios (from Richie, this volume). Such yield projections were given for Illinois and surrounding states. (These are discussed below.)

4. They were shown projected prices (discussed below) for corn and soybeans based on projected yields (from Adams, this volume).

5. They were briefed on the conceptual model discussed above, which was used to organize retrieval of expert knowledge. Experts were asked to respond specifically to this model. In responding, experts were required to provide all assumptions, facts, and heuristics brought to bear in identifying potential farmer adjustments to climate change. These are to be represented as a knowledge base of farm-level adjustments.

After results from the knowledge engineering sessions were synthesized they were portrayed in diagrammatic form. In this form, they might be thought of as a simple systems model. As such, they were presented to the experts for evaluation and resolution of conflicts of opinion between experts. When I identified a conflict of opinion, it was pointed out to the two experts. Fuller explanations of the item of conflict were sought from each expert. Often this additional clarification was sufficient to resolve the conflict. For example, there was a conflicting opinion on whether planting densities would rise or fall in response to a particular climate scenario. After receiving clarification on this issue, I determined that both experts agreed that planting densities will rise over the long term but at a slower rate than if climate had not changed. If a conflict of opinion remained after the clarification exercise, a third expert would be consulted to evaluate the issue and either break the tie or recommend that the conflict be maintained and represented as an uncertainty in the analysis.

I presented estimated yield and price responses to climate change to the experts when they become available from other EPA researchers. The methods used to develop and analyze these projections appear elsewhere in this volume (see Richie for more on yields and Adams for more on prices).

Projected yields (both for dryland and irrigated production) from Illinois and a proximate region to the south (Missouri) were presented to experts (Table 1). Inclusion of yields from Missouri is to allow experts to see the climate effect on a competing nearby area. Projected price changes will of course be uniform across all regions. Projected prices are shown in Table 2.

The experts were provided with these projections at the same time they were provided with the results. They were asked to evaluate the systems model in light of the yield and price projections. Thus the results appearing in this report incorporate the experts' consideration of projected yields and prices and their effects on adjustment/adaptation strategies.

It is useful to make a distinction in this study between changes in farm production which I represent as adjustments versus changes which I represent as adaptations. Adjustments are meant as the fine tuning of

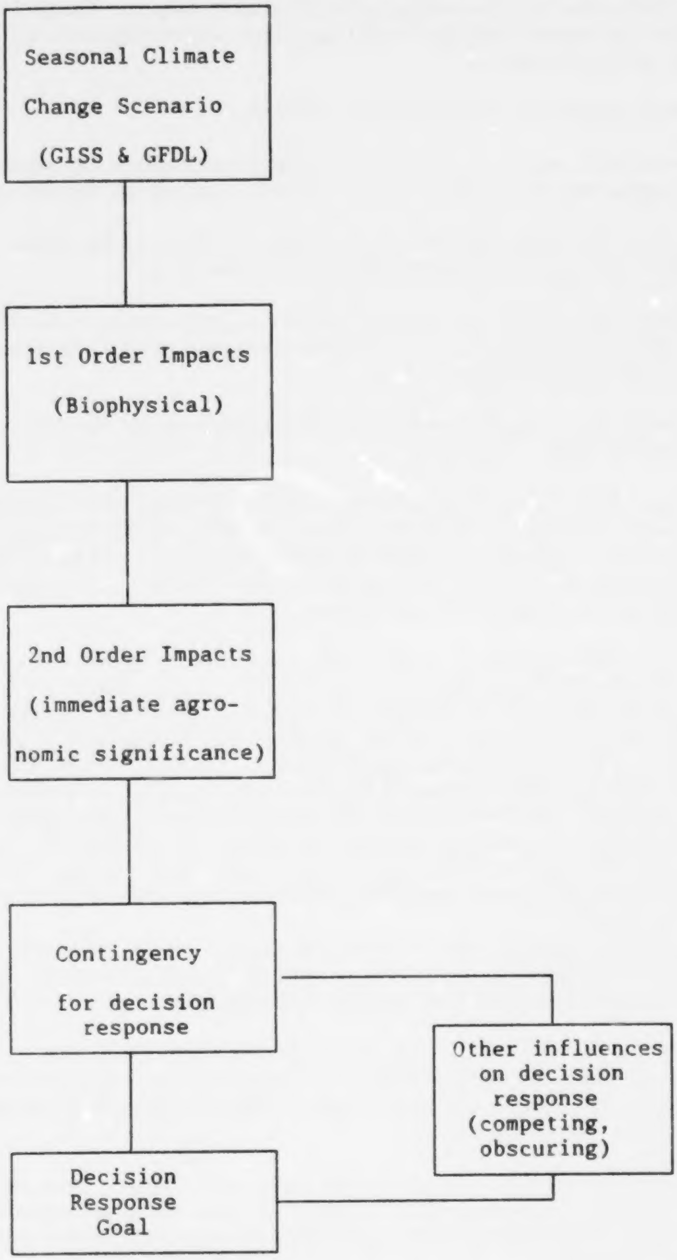
Seasonal Climate
Change Scenario
(GISS & GFDL)
1st Order Impacts
(Biophysical)
2nd Order Impacts
(immediate agronomic significance)
Contingency
for decision
response
Other influences
on decision
response
(competing,
obscuring)
Decision
Response
Goal

Figure 2. Farm level adjustments knowledge acquisition framework.

Table 1. Projected Crop Yields (from Ritchie, this Volume)

Location and Crop	Baseline Yield (Kg/Ha)	GISS $2xCO_2$ Yield (Kg/Ha)	GFDL $2xCO_2$ Yield (Kg/Ha)
Peoria dryland corn	7,429	6,517	2,427
Peoria irrigated corn	12,709	10,517	6,196
*St. Louis dryland soybeans	2,090	2,058	1,107
*St. Louis irrigated soybeans	3,407	3,167	2,630
Springfield, MO dryland corn	6,069	6,674	4,805
Springfied, MO irrigated corn	11,632	8,398	6,923
Springfield, MO dryland soybeans	1,772	1,921	1,165
Springfield, Mo irrigated soybeans	3,244	3,024	2,596

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*St. Louis soybean yields were used since Peoria soybean yields were unavailable at this writing.

Table 2. Projected Crop Prices (from Adams, this Volume)

Crop	Baseline Price	GISS $2xCO_2$ Price	GISS $2xCO_2$ % of baseline	GFDL $2xCO_2$ Price	GFDL $2xCO_2$ % of baseline
Corn	2.68	3.10	116	5.95	222
Soybeans	5.78	6.19	107	14.21	245
Sorghum	2.58	3.74	144	5.00	193

on-farm production processes already in place. Examples include changes in tillage practices, planting dates, and varieties. These are not likely to result in major investments in new machinery or radically different farming practices. Adaptations, however, are more fundamental and long term. They represent changes to production operations which were not previously in place on the farm. Examples include changes in crop species, introduction of irrigation, and even farm abandonment. The distinction between adjustment and adaptation is useful in assessing the feasibility of continuing to grow corn in Illinois if the climate changes. Adjustments imply that corn could remain feasible under climate change from an agronomic standpoint. Adaptations suggest that corn would be only marginally feasible or not be feasible at all.

Study Assumptions

A number of constraining assumptions were made in developing the analysis. These assumptions were partly to simplify what is an obviously complex task and partly to keep this analysis consistent with complementary initiatives of the the U.S. EPA's agricultural effects report. Many assumptions were derived in committee during earlier group planning exercises. Key assumptions were the following:

1. GCM climate change scenarios are prescribed by EPA. EPA principal investigators were provided three GCM scenario sets. These included the NASA/GISS and Princeton/GFDL model output for atmospheric CO_2 doubled over preindustrial levels. An additional GISS run provided 10-year transients beginning today and running to CO_2 doubling. The transient run was not included in this research. The technique for adapting these scenarios to Illinois was prescribed by EPA study organizers. This is discussed below for the $2xCO_2$ scenarios.

2. Technology is held constant. As agreed in earlier planning meetings, technology is to be kept at current levels. In this study, this was interpreted to mean that new technology not currently available (e.g., crops genetically engineered for CO_2 increase and climate change) might not be included, but that current technological trends not yet fully adopted on all or most farms (e.g., increasing on-farm mechanization) might be included in the analysis.

3. Corn as initial crop of choice. Corn (or corn-soybean rotation) is assumed to be the first choice of producers prior to imposition of a climate change. However, shifting from corn to some other crop or shifting out of production altogether are considered valid responses to climate change.

4. Direct effects of CO_2 not considered. The potential direct impact of increasing atmospheric CO_2 levels on plants, such as increased plant water-use efficiency, though important, is not explicitly considered. This constraint had to be imposed because none of the CO_2 direct effect results were available from the crop modelers involved in the study at the time of this writing.

5. Market prices increase but movement in overall costs of production are unknown. There are conflicting views as to what climate change will do to commodity prices. In a paper for a forthcoming Resources for the Future book, Easterling, Parry and Crosson posit that overproduction in the western world will continue to plague grain production (even with climate change) and that some countries may benefit agriculturally from climate change. How prices will respond is unclear, though a fall is not out of the question when global effects of climatic change are considered. Given the uncertainty surrounding prices, the current study was conducted under an initial assumption of no relative change in market prices. This assumption is relaxed later and projected price increases derived by Adams for this report are introduced.

I assume production costs to be relatively unchanging. It is not easy to justify this assumption within the framework of this study since I assume constant technology. In reality, however, if productivity is permitted to continue to increase on average in the future as it has in the past -- and we think it will (Easterling, Parry and Crosson, 1989) -- and provided environmental costs are equitably managed, there is little reason to expect production costs to rise, climate change apart. I do stress, however, that climate change may put pressure on some costs to rise and thus affect how certain decisions are made.

6. Government programs continue. This may be the weakest of our assumptions. Some speculate that the protectionism currently practiced in the U.S. will give way to freer market-driven trade. Moreover, growing emphasis on environmental protection and resource conservation are likely to have increasing influence on farm level production practices. However, formal policies have been demonstrated to be slow to change (e.g., the General Agricultural Trade and Tariff Agreement, GATT, was implemented in the late 40's and remains the basis for many of today's farm support policies). To project new policies not even under consideration today would prove to be an almost intractable problem. Thus, for this analysis, we assume no change in legislation or executive agency practice, but that positive attitudes toward resource conservation and environmental protection will continue to influence on-farm production practices.

7. All biophysical impacts except yields are subjectively determined. This is the assumption most easily relaxed in this analysis. In the initial conduct of this study experts were asked to suggest how the climate change scenarios might affect growing conditions. The basis for this request rests on the experts' perceived skill in anticipating crop problems based on a limited amount of climate information. Clearly this is not the best available method of assessing the kinds of impacts which farmers may face and be forced to adjust to. In fact, as crop simulation model yield projections under climate change became available from other EPA investigators, such projections were used in this study.

Perhaps the greatest limitation of this analysis lies in the subjective and qualitative nature of the research design. Though intensive efforts were made to create an objective knowledge acquisition protocol, including informing experts of the bounds of known facts about climate change and accompanying impacts, the fact remains that there is much expert opinion in the results. These results are a useful first approximation of steps corn producers can be expected to take, under the aforementioned constraining assumptions, in responding to the various impacts of climatic change.

Future research will seek to provide more quantitative understanding of the likelihood of certain adjustments being made. Expert knowledge gained from the above exercise will be coded into an expert system computer program. Efforts are under way to integrate the farm level decision analysis with mechanistic crop models and outputs of market level economic models. This can all be incorporated into a single integrated expert system (as discussed by Coulson et al., 1987). The expert system could then be used with actual decision makers to record how they would actually respond to simulated farm conditions.

CHAPTER 3

CLIMATE CHANGE SCENARIOS

Climate change scenarios used in the case scenario analysis were constructed from the NASA/GISS and GFDL models. Specifically, monthly mean temperature averages and monthly precipitation totals for a $2xCO_2$ climate change were derived for a representative point in Illinois. This was done in a two-step process. First the ratio of monthly climate under a $2xCO_2$ run to monthly climate in a control run (simulation of present climate) is calculated from the GISS and GFDL models. Second, these ratios were multiplied by the actual average monthly temperatures and precipitation totals to calculate the marginal amount of temperature and precipitation change. These monthly temperature and precipitation changes were added to actual current monthly normals to produce scenarios of $2xCO_2$ climate in Illinois. Peoria was chosen as representative of the most productive corn growing regions in Illinois. Thus the actual (observed) climate data is from Peoria.

Figure 3a-c shows the monthly plots of $2xCO_2$ temperature and precipitation for the GISS and GFDL model runs. The current monthly normals are plotted on each figure for comparison.

Temperatures are consistently elevated throughout the year in the $2xCO_2$ GISS scenario, with a small peak occurring in September. Precipitation is somewhat below current normals during the late summer and fall but above current normals from winter to mid-summer.

Temperature changes in the GFDL $2xCO_2$ scenario were similar to those of the GISS scenario except for one important difference: temperatures during the agronomically critical mid-summer are considerably higher in the GFDL scenario. GFDL precipitation changes were markedly different from GISS changes in both sign and magnitude. According to the GFDL model run, precipitation during the mid-summer would be reduced considerably. This pattern would remain in effect until late fall. In late fall precipitation increases to slightly above the current normal until early summer.

The scenarios given to the experts were limited to these monthly changes rather than weekly or daily changes in order to avoid information overload. Moreover, the experts were to suggest how, in view of their experience with the Illinois climate, these monthly changes might be reflected during shorter periods within months. Were further time and resources available to do so, these scenarios could be constructed to reflect climatic conditions during periods when crops are particularly sensitive such as during silking and tasseling. Nonetheless, it was felt that much useful information could be derived with monthly scenarios.

One serious concern deserving of comment here exists in the analytical structure. Some of the more extreme climate changes (especially in the GFDL scenario) might exceed the range of experience of the experts. That is, the average climate changes in the $2xCO_2$ scenario could be greater than even the extremes that are occasionally experienced in Illinois's current climate. Useful information about adjustments should be extractable under these conditions as well. Experts pointed out that corn is currently grown outside Illinois under climatic conditions that are similar to the Illinois GFDL $2xCO_2$ climate (e.g., southwest Texas). Moreover, both experts were knowledgeable of corn production in such regions. Even if experts were not experienced in climates of other regions, it can be argued that when experts are asked to consider conditions outside their own experience with Illinois climate, they will reason from the most extreme events that they have experienced. We cannot exclude the possibility that, sometime between now and $2xCO_2$, extremes matching the experts' outer range of experience will occur. Thus, their response may represent an outer range of experience, admittedly less extreme than $2xCO_2$, but a scenario that will likely occur some time in the future.

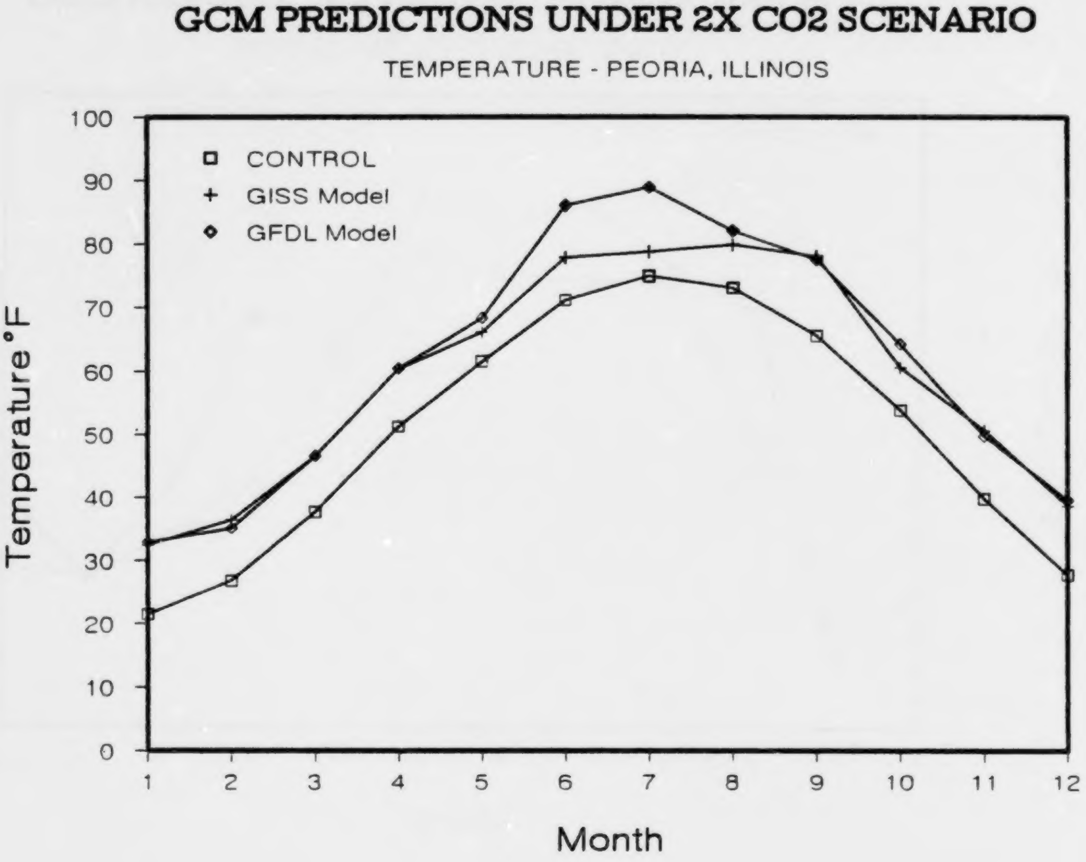

Figure 3. GCM climate scenarios for Peoria, Illinois - (a) temperature.

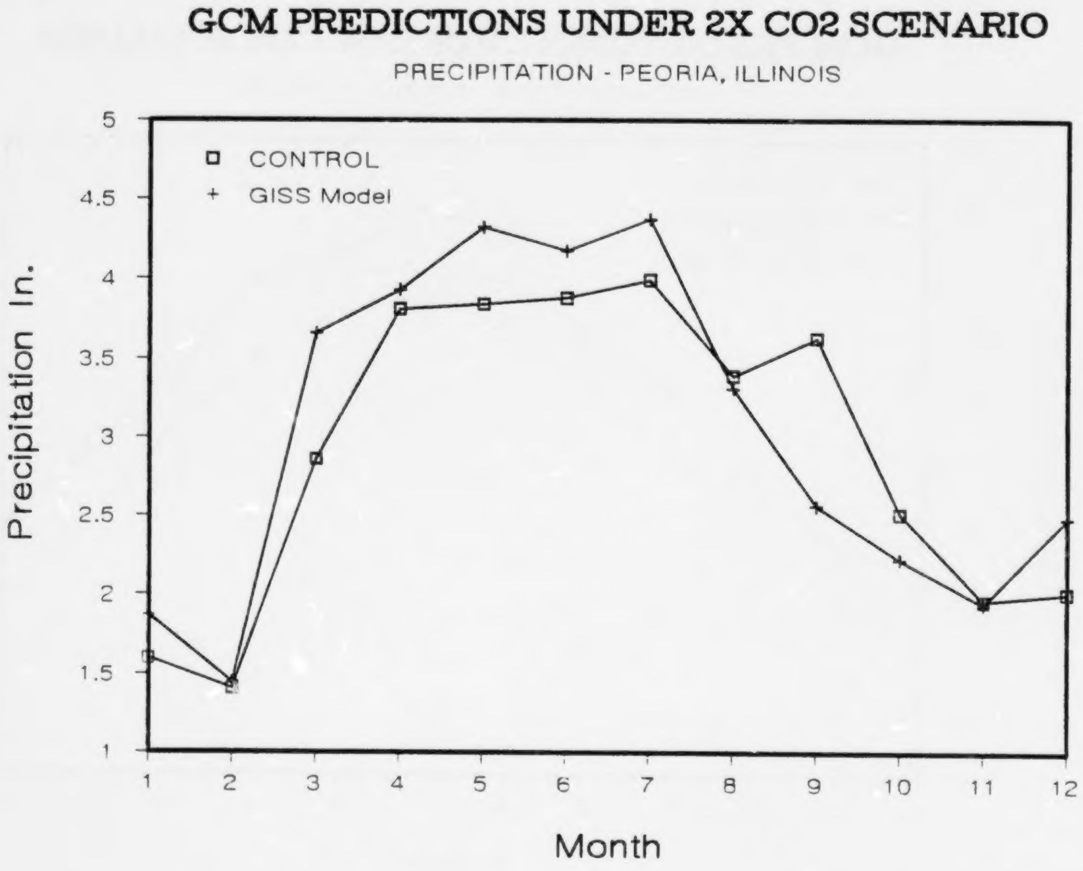

Figure 3. GCM climate scenarios for Peoria, Illinois - (b) precipitation - GISS.

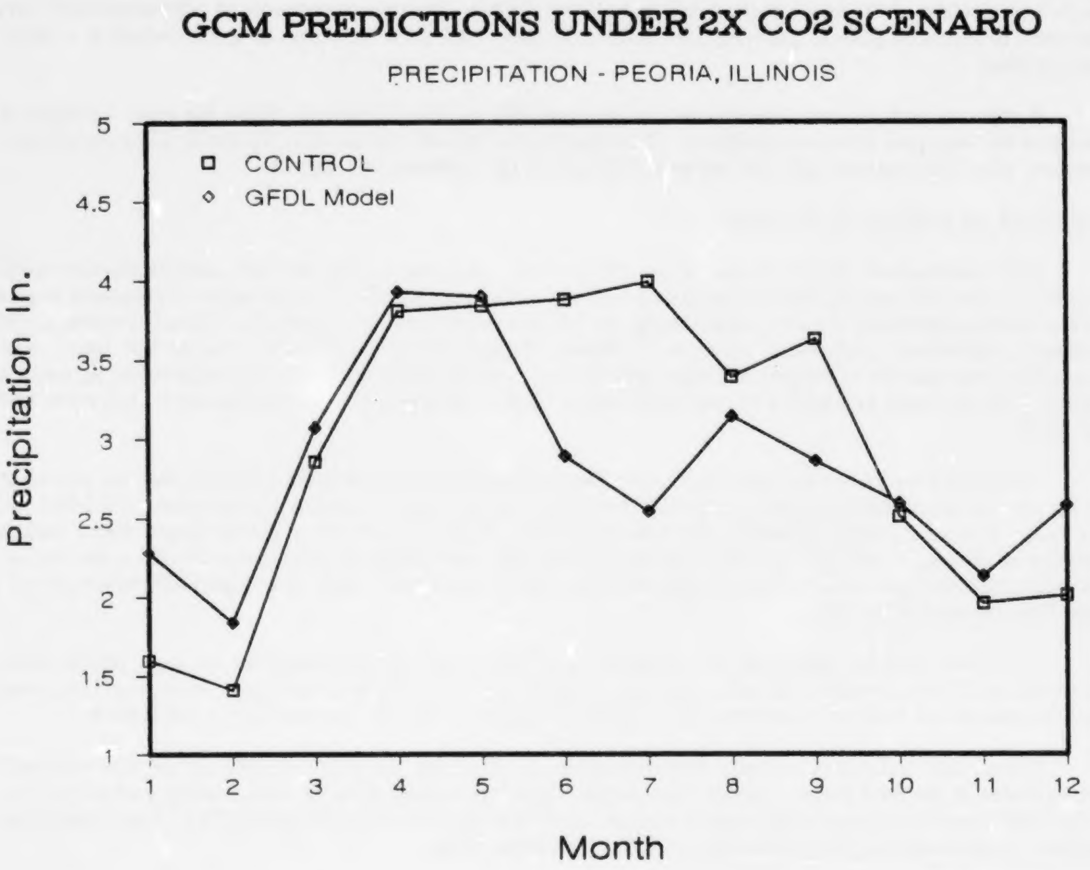

Figure 3. GCM climate scenarios for Peoria, Illinois - (c) precipitation - GFDL.

CHAPTER 4

RESULTS

Results of the knowledge aquisition sessions were represented diagrammatically in a series of flow models of potential climate impacts and farmer adjustments. It is important that these results be interpreted as representing how an Illinois corn producer might adjust production practices and what related issues he might face if the climate were to shift suddenly to a new equilibrium state. An instantaneous response of climate is implied by doubling CO_2 levels in the GISS and GFDL GCMs. Though assessments of adjustments are best discussed in terms of gradual warming over several decades, analysis of response to quick change is a useful starting place.

A separate analysis was done for certain agronomically meaningful periods within the year. Linkages of decisions between periods were considered. These periods are (a) fall post-harvest; (b) spring and early summer preplant, plant; (c) summer anthesis and grainfill; and (d) fall drydown and harvest.

Analysis of the GISS 2xCO_2 Scenario

Fall Post-Harvest. Upon review of the GISS 2xCO_2 year, the experts felt that corn production could remain feasible with only adjustments to existing technologies already in place on most farms. Assessment begins with potential adjustment decision paths during the fall post-harvest period (Figure 4). Tillage operations and fertilizer applications, each being sensitive to climate change, are normally under way at this time. The immediate consequence of warmer and drier post-harvest conditions is a drier soil. The immediate agronomic impact is an increased probability of more field days -- days in which farmers can move heavy equipment into the fields.

If farmers have grown accustomed to expecting wetter conditions (fewer field days) during the upcoming spring preplanting and planting period (as GISS predicts), then the greater number of post-harvest field days will encourage more fall tillage operations and fall-applications of potash and phosphate fertilizers where such is possible in Illinois. In effect, more fall field days provide the opportunity to compensate for the fewer spring field days expected. But this strategy is somewhat dependant on soil type. Soils in southern Illinois are not and would not be worked in fall.

If farmers grow to expect warm wet winters (as GISS predicts), the incentives to apply nitrate-based fertilizers in fall will decrease. In such conditions denitrification and nitrogen leaching increases and the usual effectiveness of fall fertilizer application (i.e., allowing nitrogen to diffuse into the soil) is diminished.

Nonclimatic influences on these decisions derive largely from the growing concerns for environmental management at the farm level. Any increase in fall tillage will conflict with soil conservation policies such as T-by-2000[3] and with general conservation concepts implicit in the Food Security Act of 1985. These conflicting interests might lead to a general increase in fall conservation tillage.

Environmental concerns, especially pertaining to agricultural chemicals in runoff, would likely reinforce a reduction of fall application of nitrate-based fertilizers. However, phosphate and potash-based fertilizers are less mobile in the soil than nitrates and, thus, might engender less concern.

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[3] T-by-2000 is an expression describing attempts by states to encourage farmers to follow practices which reduce soil erosion to rates which fall within certain tolerances as described by a model known as the Universal Soil Equation.

Fall Post-Harvest
(October-December)

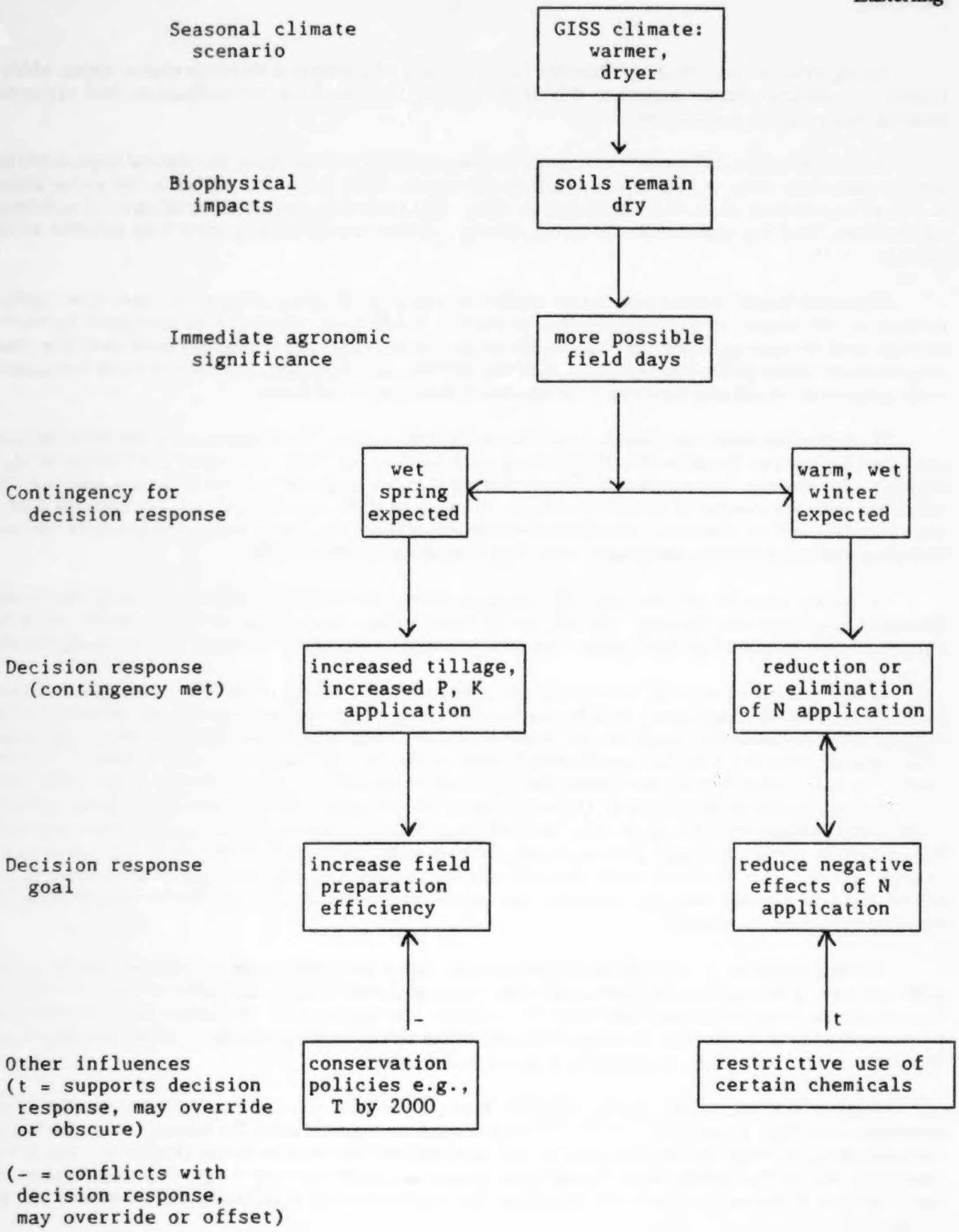

Seasonal climate scenario
GISS climate: warmer, dryer
Biophysical impacts
soils remain dry
Immediate agronomic significance
more possible field days
Contingency for decision response
wet spring expected
warm, wet winter expected
Decision response (contingency met)
increased tillage, increased P, K application
reduction or or elimination of N application
Decision response goal
increase field preparation efficiency
reduce negative effects of N application
-
t
Other influences (t = supports decision response, may override or obscure)
(- = conflicts with decision response, may override or offset)
conservation policies e.g., T by 2000
restrictive use of certain chemicals

Figure 4. GISS fall post-harvest adjustments.

Spring Preplant and Planting. Farmers face a number of production decisions during spring which are directly or indirectly climate-dependent (Figure 5). These decisions focus on fertilization, field preparation, planting, and pesticide applications.

According to the GISS scenario spring will be warmer and wetter than now. Biophysical impacts will likely include soils more often at field capacity early in the season. Soils may warm earlier in the spring although wetter soil would likely offset such warming to an extent. The immediate agronomic significance of such impacts will be fewer field day opportunities in spring although warmer conditions may allow field activities to begin earlier.

If nitrogen-based fertilizers cannot be applied so readily in fall, more nitrogen will have to be applied in preplant or side dressed in early summer than at present. Additionally, there may be agronomic incentives to increase total nitrogen application in order to take advantage of a shift toward generally more favorable climatic conditions and higher yields. The experts emphasized, however, that increasing concern over water contamination from agricultural runoff may limit use of nitrate-based fertilizers in the future.

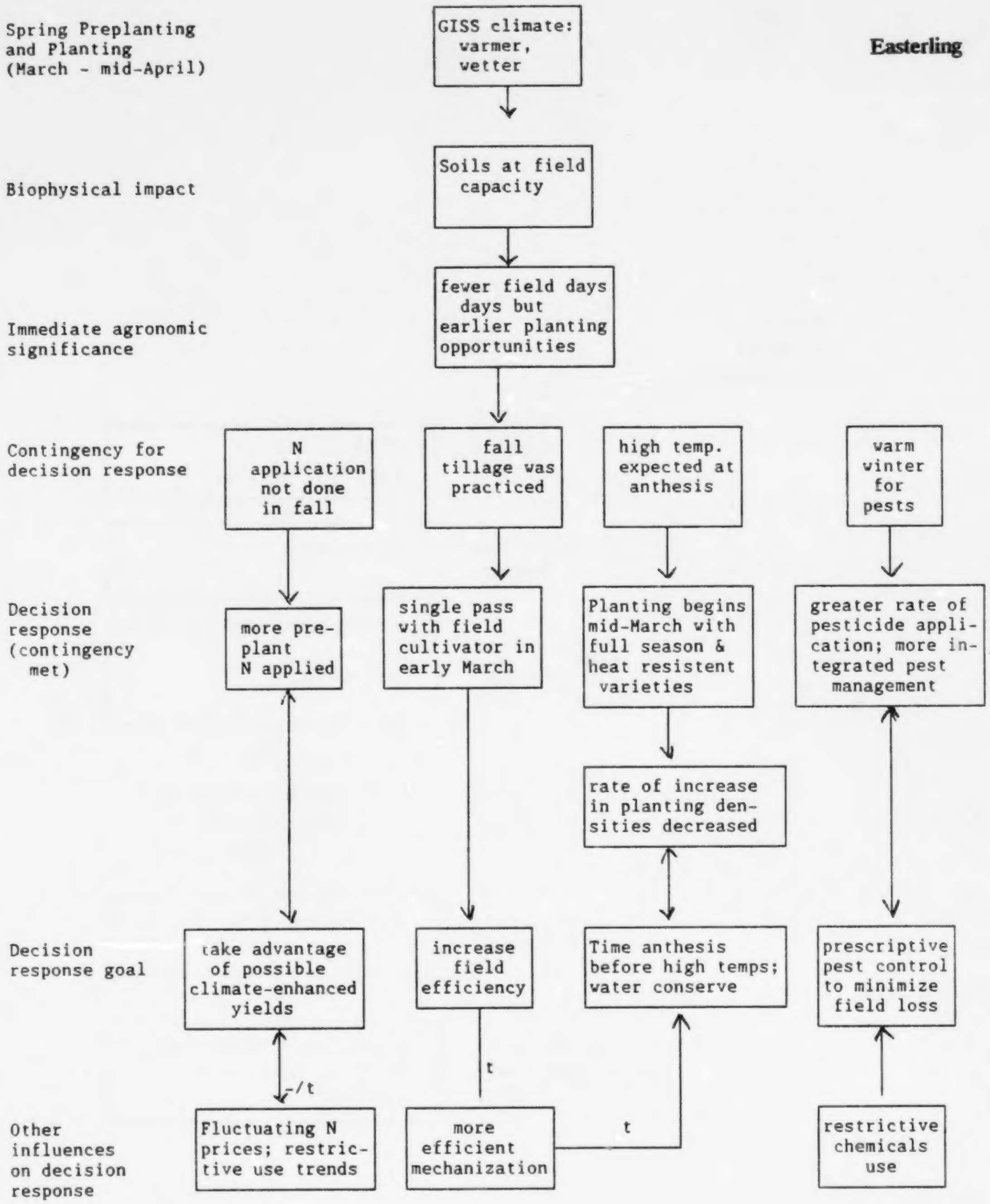
If the previous winter were warm (as predicted by GISS) and warm conditions are expected to occur over the upcoming summer (predicted by GISS) then pest populations are likely to increase (see Skinner et al., this volume). The decision response would favor increased pesticide applications, even if farmers embrace "apply only when pests are present" practices. Growing restrictions on the uses of agricultural chemicals (as discussed above) conflict with this outcome. Intensified development of integrated pest management practices (innovative biological and nonchemical management technologies) provides an alternative.

If tillage is done the previous fall, only a single pass over the field with a cultivator in early March will be needed as preparation for planting. Not only will field preparations begin about two weeks earlier, but a single equipment pass will speed up field preparation compensating for the aforementioned loss of spring field days.

If high temperatures occur at anthesis (as predicted by GISS) then decisions as to choice of variety, planting date, and planting density must be made in the spring. High temperatures during anthesis, especially if plant water requirements cannot be met, would stress plants and increase the likelihood of poor pollination. This would likely be due to lack of coordination between pollen shed and silk emergence. Losses in yield would follow. In anticipation of such conditions, planting could begin earlier taking advantage of the earlier spring. Thus anthesis would occur prior to the highest summer temperatures. Earlier warming in spring mentioned above could facilitate this strategy provided that soil temperature thresholds for germination also occur earlier. Because of the potentially longer growing season, farmers could resort more to the use of full season varieties in their crop mix. It is likely that variety diversity will be maintained on any given farm leading to a mix of full season and heat tolerant varieties. Cultivars now planted in the southern United States could become more common in Illinois, for example.

Planting densities are already on the rise on most farms and could reach a maximum density of 30,000 seeds per acre. This trend will likely continue with or without climate change. The effect of higher densities may be to make the crop more vulnerable to the dry conditions in mid-summer. If farmers alter planting density practices at all it would likely be to decrease the rate of increase in planting densities. Lower planting densities will decrease the competition of plants for available soil moisture.

Summer Anthesis. Once spring and early summer are past, there is little a farmer can do to affect production until fall. However, if previous climate-dependent decisions leave the farmer's soils with less than optimum nitrogen levels, sidedressing prior to and up to anthesis becomes an option (Figure 6). This is highly contingent on a farmer having access to specialized equipment for sidedressing the growing crop (in some cases up to the time of anthesis). There are indications that such technology is becoming more available and more widely used.


Spring Preplanting and Planting (March - mid-April)
GISS climate: warmer, wetter
Biophysical impact
Soils at field capacity
Immediate agronomic significance
fewer field days days but earlier planting opportunities
Contingency for decision response
N application not done in fall
fall tillage was practiced
high temp. expected at anthesis
warm winter for pests
Decision response (contingency met)
more preplant N applied
single pass with field cultivator in early March
Planting begins mid-March with full season & heat resistent varieties
greater rate of pesticide application; more integrated pest management
rate of increase in planting densities decreased
Decision response goal
take advantage of possible climate-enhanced yields
increase field efficiency
Time anthesis before high temps; water conserve
prescriptive pest control to minimize field loss
-/t
t
t
Other influences on decision response
Fluctuating N prices; restrictive use trends
more efficient mechanization
restrictive chemicals use

(t = support decision response; may override or obscure)
(- = conflicts with decision response may override/offset)

Figure 5. GISS spring preplant and planting adjustments.

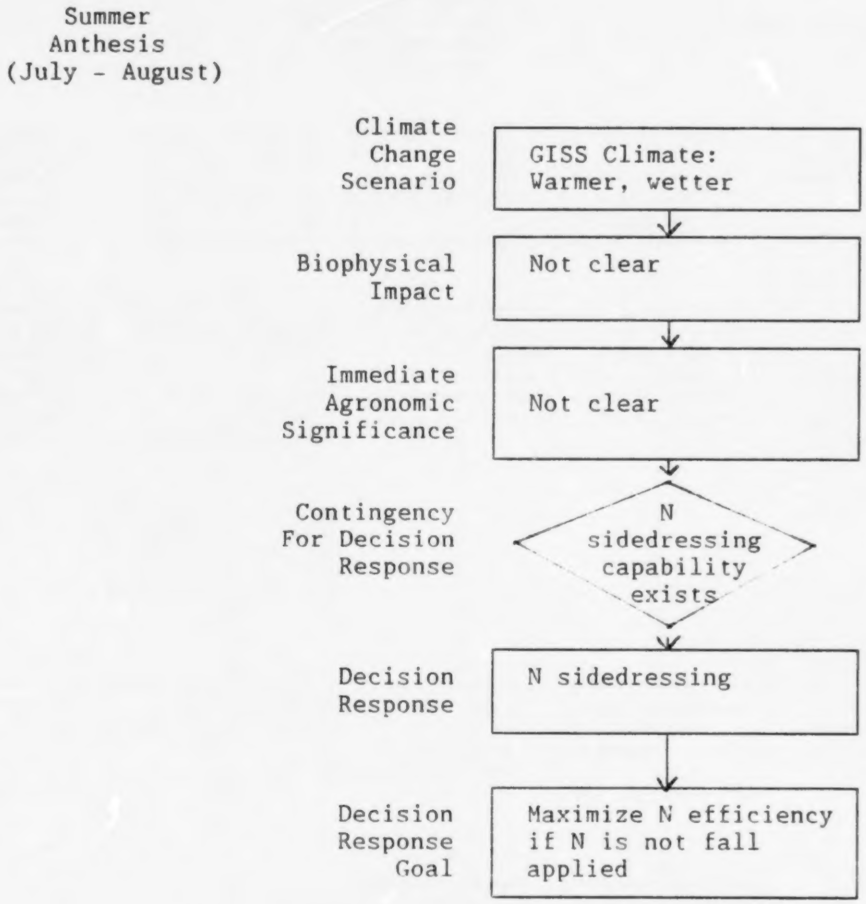

Summer
Anthesis
(July - August)
Climate
Change
Scenario
GISS Climate:
Warmer, wetter
Biophysical
Impact
Not clear
Immediate
Agronomic
Significance
Not clear
Contingency
For Decision
Response
N
sidedressing
capability
exists
Decision
Response
N sidedressing
Decision
Response
Goal
Maximize N efficiency
if N is not fall
applied

Figure 6. GISS summer anthesis adjustments.

Fall Harvest. The GISS model projects a warmer, drier climate during the early fall harvest period. The most significant biophysical consequence of this is increased evaporation (Figure 7). Harvest in Illinois would likely occur earlier in the summer. This would complement the effects of earlier planting by allowing normal or even more rapid and thorough drydown to take place. More rapid corn drydown would encourage earlier harvesting. This would result in higher quality yields. More thorough drydown would also be likely to reduce the need for expensive artificial drying procedures. Moreover, there are no readily identifiable factors that might impede adoption of these practices. The incentive to reduce costs of fuel for artificial drying would actually encourage adoption.

Analysis of the GFDL 2xCO_2 Scenario

The relatively more severe climate changes suggested by the GFDL model require a slightly different approach to the discussion of adjustment. The experts agreed that the hot and dry conditions of mid-summer predicted in the GFDL 2xCO_2 scenario would force corn producers to make major adaptations. In the logic of this analysis, these decisions would occur in fall immediately after corn harvest.

Figure 8 is a schematic of fall post-harvest decision paths available to farmers under the GFDL 2xCO_2 climate change scenario. Like the GISS scenario, the analysis begins with warm, dry conditions in fall likely to lead to more fall field days. At this point, however, the GFDL-driven decision scenario departs significantly from the GISS-driven scenario. Expectations in fall of the next season's hot, dry mid-to-late summer would likely force farmers to choose among three initial alternatives. Two of the alternatives would involve abandoning corn production totally. These alternatives represent major adaptations.

(1) Changing crops or land use. If climate changes were to shift comparative advantage to heat and low-moisture hardy crops such as grain sorghum to Illinois farmers, then Illinois farmers could conceivably switch to such crops. If productivity in these crops in nearby competing regions is unaffected or affected beneficially by climate change, Illinois farmers could be forced either to leave agricultural production altogether or to produce their corn for even smaller profits than now. In the former case, competing land uses, some nonagricultural (e.g., urban encroachment), could force lands, especially marginal lands, out of production. If corn production is to continue, however, farmers would almost certainly be forced to grow shorter season, lower yield, varieties. These varieties could probably be intercropped with a heat and moisture stress resistant crop such as grain sorghum.

(2) Irrigation. Irrigation is a potential adaptive decision. Irrigation may not be widely applicable in Illinois since groundwater availability and soil moisture holding characteristics may not be suitable in many parts of the state. For example, some soils in southern Illinois contain too much clay for effective irrigation (water simply runs off). Also, at current production costs and crop prices the operation of irrigation systems may not be economical in Illinois, even under climate change conditions. Adams (this volume) suggests sizable price increases for corn under the GFDL scenario. If he is correct, experts felt it would be reasonable to expect some increase in irrigation in Illinois under the GFDL scenario. But not all or even most farmers would be likely to acquire and operate irrigation systems.

(3) Continuing with corn. If a farmer decides to continue raising corn, especially if he uses short-season varieties possibly intercropped with grain sorghum, then the most important decision in fall would be the amount of acreage to be tilled in preparation for spring planting. The experts agreed that under the GFDL scenario, more marginally productive land would likely be taken out of crops--a logical response to anticipated higher costs and reduced productivity on these lands. Since the GFDL and GISS 2xCO_2 winter and spring temperature and precipitation scenarios are generally similar, other fall post-harvest decisions would likely be as described under the GISS results (refer to discussion in the previous section).

In connection with their implications for continued production of corn, the GISS and GFDL 2xCO_2 scenarios differ most in the summer. On the one hand, the GISS model projects higher temperatures and higher rainfall than present during the anthesis and grainfill periods (on the dates that such periods presently occur).

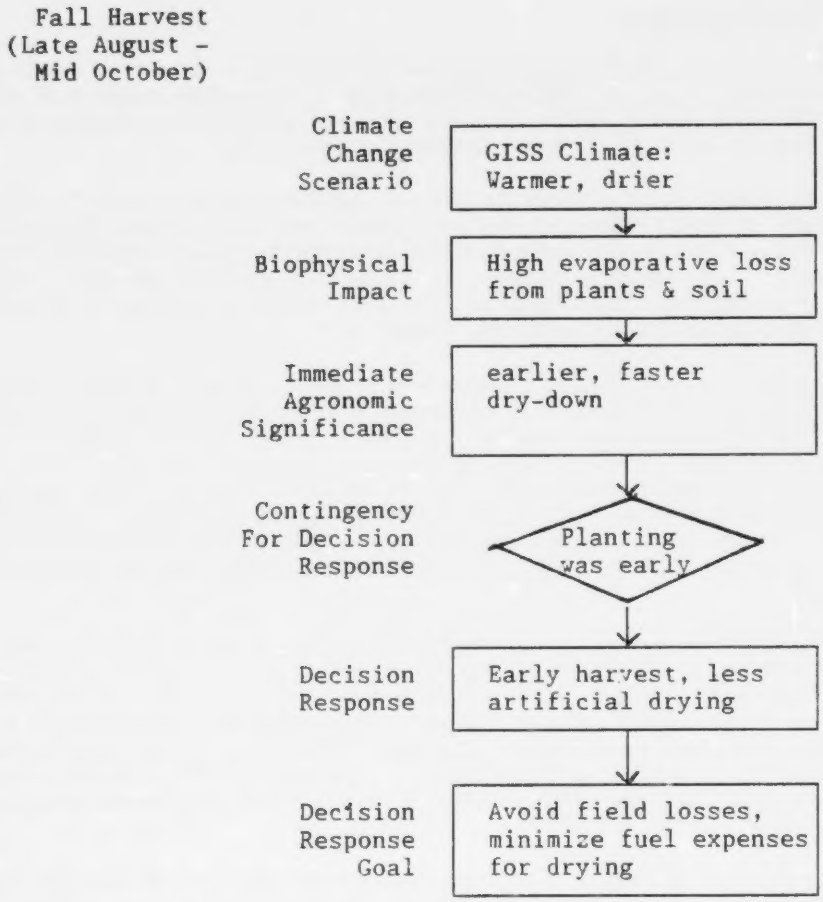

Fall Harvest
(Late August -
Mid October)
Climate
Change
Scenario
GISS Climate:
Warmer, drier
Biophysical
Impact
High evaporative loss
from plants & soil
Immediate
Agronomic
Significance
earlier, faster
dry-down
Contingency
For Decision
Response
Planting
was early
Decision
Response
Early harvest, less
artificial drying
Decision
Response
Goal
Avoid field losses,
minimize fuel expenses
for drying

Figure 7. GISS fall harvest adjustments.

Fall Corn Post-Harvest (GFDL)

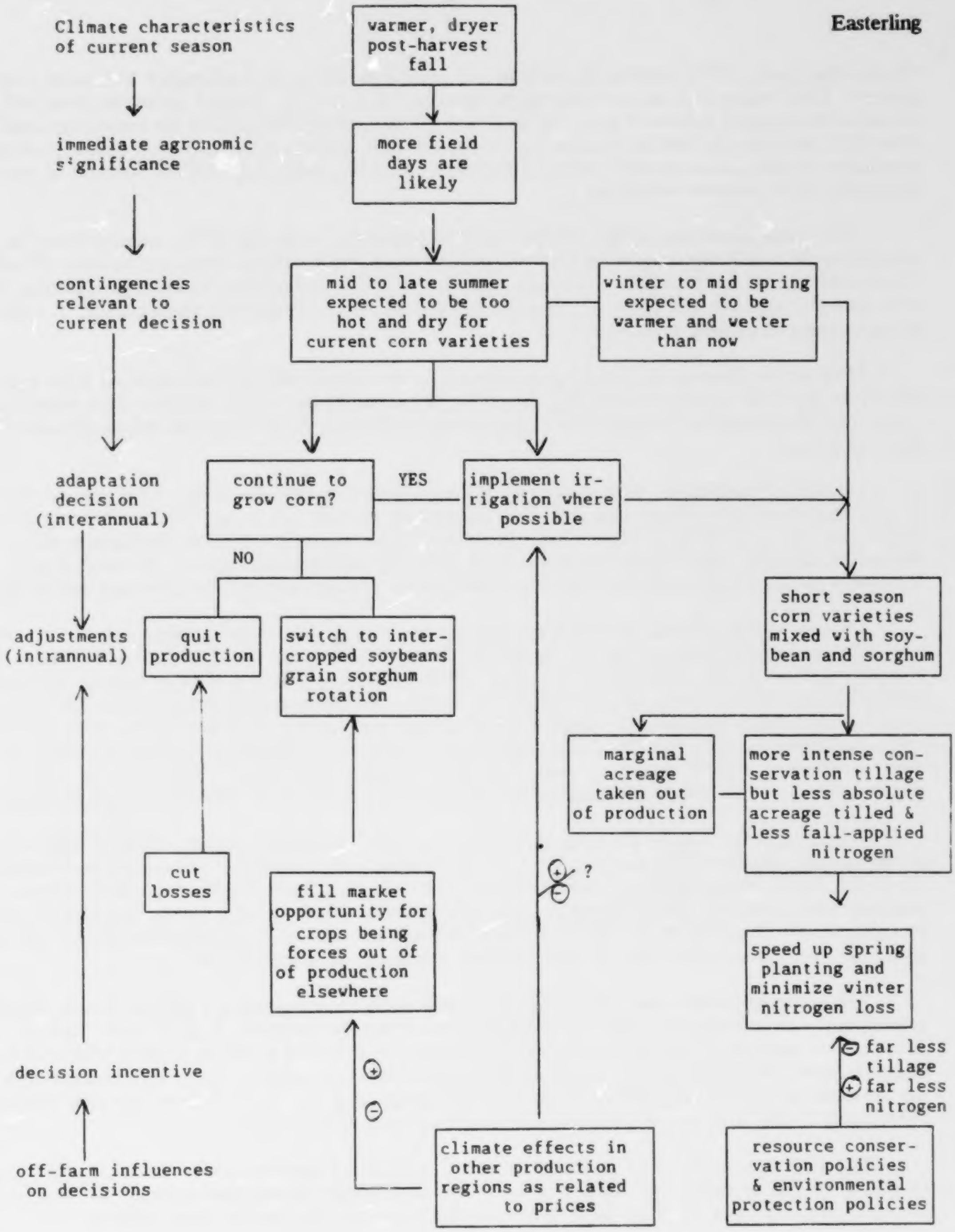

Climate characteristics of current season
immediate agronomic significance
contingencies relevant to current decision
adaptation decision (interannual)
adjustments (intrannual)
decision incentive
off-farm influences on decisions
warmer, dryer post-harvest fall
more field days are likely
mid to late summer expected to be too hot and dry for current corn varieties
winter to mid spring expected to be warmer and wetter than now
continue to grow corn?
YES
NO
implement irrigation where possible
quit production
switch to intercropped soybeans grain sorghum rotation
short season corn varieties mixed with soybean and sorghum
marginal acreage taken out of production
more intense conservation tillage but less absolute acreage tilled & less fall-applied nitrogen
cut losses
fill market opportunity for crops being forces out of of production elsewhere
⊕ ?
⊖
speed up spring planting and minimize winter nitrogen loss
⊖ far less tillage
⊕ far less nitrogen
⊕
⊖
climate effects in other production regions as related to prices
resource conservation policies & environmental protection policies

Figure 8. GFDL fall post-harvest adaptations and adjustments.

On the other hand, GFDL projects the anthesis and grainfill periods to be much higher with lower rainfall than present. Even taking into account differences between these models, farmers' spring decisions will aim to minimize the negative impacts of a wet spring and avoid the high temperatures of the anthesis-grainfill period. Most GISS strategies for dealing with the high temperatures in mid to late summer (e.g., earlier planting, lower population densities, more varietal and crop diversity) would also apply to the GFDL scenario of warmer and significantly drier summer conditions.

One major production adjustment that could be considered under the GFDL scenario would be to hold nitrogen application levels constant or even to reduce nitrogen applications in spring and summer as well as fall. The incentive to do this is twofold: (1) reduced summer rainfall would result in less nitrogen leaching, thus less total nitrogen required; and (2) lower yield expectations would encourage cost minimization. A reduction in nitrogen usage might help reduce costs.

With earlier planting and increased reliance on shorter season varieties, harvest could occur even earlier than under the GISS scenario. Aside from the probability of harvests as early as July (for short-season varieties) under the GFDL scenario, the same harvest adjustments would apply for both climate change scenarios (i.e., less artificial drying).

(4) Farm abandonment. Returning to the fall post-harvest adaptive decisions -- if the corn grower decides to quit agricultural production altogether, then the analysis ends at that point. This is obviously an extreme action, one that is not likely to occur often. However, if many make this decision the impacts will be felt far beyond the farmgate. It is beyond the scope of this study to consider these impacts. Research is under way at Resources for the Future to consider climate change impact linkages between the farm and market levels.

Changes in cultural practices that might accompany crop changes. If the decision made in fall is to switch to a different cropping pattern, then the farmer will be faced with a new set of production decisions. Double cropping, defined as the following of one crop with another crop within a growing season, is practiced in southern Illinois. For example, wheat is followed by soybeans on many southern Illinois farms. Double cropping is seen as maximizing the economic potential of the land, given agronomic constraints such as soils, climate, input costs, market prices, and so on. Double cropping is not widespread in Illinois because only a limited part of the state experiences a long enough growing season to support two crops. The areas in Illinois where wheat-soybeans double cropping is practiced are often characterized by poor soils and a longer growing season.

Wheat-soybeans double cropping is practiced in other proximate regions south of the major corn production area of Illinois. To an extent, these proximate regions currently experience temperatures approaching the GFDL $2xCO_2$ temperatures for central Illinois. Thus it is tempting to suggest that wheat-soybeans double cropping would supplant corn in Illinois as temperatures warm. However, such double cropping will likely not be widespread in Illinois under the GFDL scenario. Dry and hot summer conditions would deplete soil moisture under the wheat crop to the extent to be insufficient to support the soybean crop.

The cropping pattern that experts felt to be most likely to replace corn would be straight soybeans or possibly soybeans intercropped (grown at the same time) with grain sorghum. Both of these crops have higher moisture and heat stress tolerances than corn. Soybeans are routinely grown in rotation with corn by many Illinois farmers. Moreover, grain sorghum production practices are similar to corn production practices. Thus the switching to some combination of soybeans and grain sorghum would require less new learning and reequipping on the farm than would switching to another crop such as wheat.

Experts reasoned that with projected increases in prices for soybeans under the $2xCO_2$ GFDL climate (predicted to rise by more than 200% over today's prices), farmers would find soybeans to be profitable in Illinois even given major predicted yield decreases. Such was also the case for grain sorghum.

SUMMARIZING ADJUSTMENTS: COMPOSITE PORTFOLIOS

It is useful to compile from the previous analysis a comprehensive set of on-farm adaptations and production adjustments (call them -- a portfolio). Such a portfolio would reflect all adjustments that a farmer might make to optimize his operations in response to climate change. Influences on adjustment decisions other than climate (as discussed above) were not considered in building the portfolio. This illustrates what steps could be taken on the farm, all things being equal, to adjust production to climate change.

Table 3 shows adjustments by seasons based on the GISS 2xCO_2 climate change scenario. The bulk of adjustments will occur during the fall post-harvest and the spring pre-plant and planting periods. Only one adjustment option is available to farmers after planting and before harvest, i.e., nitrogen sidedressing.

Table 4 shows adjustments and adaptation that may follow the GFDL 2xCO_2 warming. Note that the types of adjustments to farming operations will follow somewhat from choice of adaptation. For example, if farmers choose to continue with growing corn (but they adapt with short-season varieties) then nitrogen will still be applied although such application might be eliminated in fall (adjustment) and reduced in spring and summer (adjustment).

These scenarios, though qualitative, could provide information for crop simulation models on how to manipulate certain variables (e.g., varieties, planting dates, planting densities). This would allow alternative on-farm adjustments and adaptations to be reflected in the crop models. The result would be crop model estimates of productivity, modified by management response, as an alternative to productivity estimates generated by simply varying climate and some other less systematically chosen model components. Moreover, as the adjustments analysis is refined, the reliability of estimates of crop yield response to climatic change would improve.

Table 3. Composite Adjustments to Optimize For Climate Only: GISS Scenario

	Season	Adjustment
1.	Fall Post harvest (October-December)	. increased tillage (mostly conservation) . increased application of phosphates and potash . reduction or elimination of fall-applied nitrogen
2.	Winter (December-March)	. none
3.	Spring Pre-plant and plant (March-April)	. reduction of field preparation to single pass with field cultivator (early March) . multiple varieties but more full-season and heat resistant (planting begins mid-March) . slower rate of increase in planting densities . none nitrate fertilizer applied . more pesticides applied (some increase in integrated pest management)
4.	Late Spring-Early Summer (Mary-June).	. none
5.	Summer Anthesis (late June-July)	. nitrate fertilizer sidedress (when possible)
6.	Late Summer	. none
7.	Fall Harvest (September-October)	. earlier harvest . less artificial drying

Table 4. Composite Adjustments to Optimize For Climate Only: GFDL Scenario

__Adaptations__

Alter crops planted to a mix of short season corn varieties and soybeans/grain/sorghum which are better adapted to heat and moisture stress than full season corn

Plant only on best land (reducing total acreage planted) to minimize climate stresses on productivity*

Establish or expand irrigation when water supplies exist and soils are amenable to irrigation in order to moisture and heat stress in mid-summer

__Adjustments__

Increased fall conservation tillage to shorten field preparation activities in spring

Decreased fall applied nitrogen to reduce winter leaching and denitrification

Earlier planting to avoid mid-summer high temperatures and aridity

Lowered rate of increase in offset planting densities to decrease competition for moisture

Increased pesticide applications and integrated pest management practices) to control warming-induced insect and weed population expansions

Less nitrogen applied in spring partly to reflect lowered nitrogen leaching in a drier summer and partly to reflect need to minimize input costs

Earlier harvest and less artificial drying in order to benefit from warm and dry late summer and early

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*If input costs (e.g. fertilizer, pesticides, seeds) rise, then more land, not less, might be brought into production as a substitute for more expensive inputs (Crosson, 1986).

CHAPTER 5

INTERPRETATION OF RESULTS

From the foregoing discussion, it is clear that climatic changes occurring within the bounds of the GISS and GFDL $2xCO_2$ model runs will affect Illinois corn production. Though no attempt is made here to predict the economic feasibility of corn production in Illinois after climate change, I argue that farmers will try to adapt and adjust to climate as it changes. Moreover, knowledge of how such adjustments and adaptations might take place is necessary to calculate the net effect of climate on farmers and their crops. In the following paragraphs, I provide a set of conclusions on farmer responses to climatic change which are based on the above analysis. Such responses are divided into categories of general conclusions, specific adjustment possibilities, and specific adaptation possibilities.

General Conclusions

1. Adjustments to existing production practices are the first line of defense against climate change. Production practices currently in use by corn producers can be altered with little cost to the farmer to cope with some types of climatic fluctuation.

Examples of such adjustments include altering planting dates, crop mixes, tillage practices, and fertilizer applications (these are elaborated below). This analysis suggests the possibility that, in some scenarios of climate change, such adjustments could totally eliminate negative climate impacts or even create a positive growth situation. The net effect of climate change on corn production after adjustment(s) are made by farmers will be significantly different from the effect of climate change without adjustments.

2. More severe climatic changes are likely to make major adaptations necessary. If climatic conditions were to become as hot and dry during the summer growing season in Illinois as projected by the GFDL model, then farmers who are used to raising full-season corn will be forced to adopt production practices quite different from those in use today. Such adaptations would be necessary to deal with the potentially high heat and moisture stress conditions likely to accompany such climatic changes. Examples of adaptations that are likely to be made include installation and use of irrigation systems; changes in crop mix to include some combination of short- season corn, soybeans, and grain sorghum; and removal of some marginal land from production on a given farm.

3. Climate changes in nongrowing season parts of the year will be important, and nongrowing season adjustments are likely to follow. Climate change will occur in all seasons. Indeed, in the Northern Hemisphere mid-latitudes, changes may be most dramatic in winter. Climate changes in the nongrowing season (fall post-harvest and winter) will affect some adjustment decisions. For example, a warmer and wetter winter would increase nitrogen leaching and denitrification, thus leading to a likely reduction of pre-growing season fall-applied fertilizer.

4. Changes in regional comparative advantage will determine the extent of adjustment versus adaptation. The effect of climate on agricultural regions competing with Illinois will directly influence how adjustments and adaptations are made by Illinois producers. Economics apart, neither the GFDL nor the GISS $2xCO_2$ climate scenarios would preclude corn from being raised in Illinois if appropriate adjustments (e.g., earlier planting, altered tillage) and adaptations (e.g., irrigation, short-season varieties) are made. However, when economics come into play, many of these adjustments may raise production costs high enough to make corn production unprofitable relative to other regions or other crops. On the one hand, if other production regions are similarly adversely affected by the climate change and world demand for food and fiber cannot be met, then market prices could rise. Such price increases would encourage more extensive efforts to adjust and adapt production to the climate change. On the other hand, if comparative advantages begin to weigh more heavily in favor of other regions as climate changes, prices do not go up, and necessary adjustments by Illinois farmers become too costly, the only strategy left for Illinois farmers is to leave farming altogether or, more likely, to choose a new crop to

grow.

If prices for crops uniformly rise, as predicted by Adams (this volume), and input prices do not rise significantly, then adjustments are likely to be extensive in Illinois. I consider the sorts of specific adjustments and adaptations that might be in store in the following two sections.

Specific Adjustment Possibilities

A number of adjustments to existing production practices could be made by Illinois corn producers in response to changes in climate:

1. Changes in tillage practices. This research points to increased fall conservation tillage in Illinois. This would offset the negative effects of a smaller possible number of field days in the following spring planting season and would take advantage of dry conditions in the fall season. Though this response may not, by itself, have a large effect on yields, it will contribute in a significant way to how farmers may respond.

2. Less fall-applied nitrogen. Questions aside about the continued production of corn in Illinois under climate change, less nitrogen is likely to be applied in fall. If nitrogen-fixing legumes such as soybeans replace corn in Illinois, then less nitrogen use needs no explanation. However, if corn and other crops which benefit from nitrogen application continue to be grown, then the explanation for less fall-applied nitrogen is the desire to avoid leaching and denitrification during the warmer (and possibly wetter) winter.

3. Planting earlier in the spring. It will benefit farmers to plant corn earlier in the spring than at present. Earlier planting will result in the occurrence of anthesis (a period of high temperature and moisture stress sensitivity) earlier in the summer when temperatures and soil moisture levels are less likely to be at stress levels. Earlier planting could be enhanced by warmer spring temperatures. However, the warmer spring temperatures could be offset somewhat by the greater heat storage capacity of a wetter soil (wetter from higher than current precipitation in winter), i.e., as soil moisture increases, more energy is needed to raise the temperature of the soil.

4. Changes in corn varieties. Climatic change will encourage farmers to alter the corn varieties planted either to maximize potentially beneficial climate changes or to minimize potentially negative climate changes. If planted earlier than at present, there is a possibility that high yielding, full-season varieties would do well under the GISS $2xCO_2$ summer climate. Also, if planted earlier than now, low yielding short-season corn varieties could be grown under the relatively harsh GFDL $2xCO_2$ summer climate.

5. Lower planting densities. Potentially drier soils during summer will likely lead to changes in planting densities. Lowering the number of plants per unit area would conserve soil moisture. Given that planting densities have been increasing steadily in recent years, it is likely that densities will be higher than at present but not as high as they would have been without climate change.

6. More attention to pests. Warmer temperatures are likely to stimulate greater pest problems (this is handled more extensively by Skinner et al., this volume). It would be reasonable to expect farmers to respond with some increase in pesticide use but perhaps accompanied by greater emphasis on integrated pest management practices.

7. Earlier harvest. If planting does occur earlier in the spring than now, it follows that harvest will begin earlier than now. This is especially true if short-season varieties were planted in spring. Also, changes toward warmer and drier late summers and early falls are likely to favor earlier corn maturation and to accelerate drydown. Not only would farmers be able to harvest earlier than now, but there is likely to be less need for artificial drying.

Specific Adaptation Possibilities

1. Altered crop mixes. Depending upon the exact nature of climatic change, farmers are likely to change not only the varieties of corn to be raised, but also to alter the types of crops grown. Crop mixes could become more diverse with likely combinations (either intercropped or annually rotated) of corn, soybeans, and grain sorghum. If corn is grown under the GFDL $2xCO_2$ scenario, then almost certainly it will be a short-season variety.

2. Increased irrigation. According to the experts, current climatic and economic conditions would support use of irrigation in Illinois approximately 3 years out of 10 years. Climatic changes, especially changes which leave soils drier during summer than now, will likely lead to increased use of irrigation in Illinois. Increased use of irrigation is supported by projected price increases for all crops likely to be grown in Illinois. However, not all farmers can be expected to turn to irrigation as climate changes. Insufficient water supply and nonirrigable soils will limit where irrigation may come into practice. Moreover, even with severe climatic changes, some crops may be profitably grown without irrigation (e.g., soybeans, grain sorghum).

3. Marginal land taken out of production. If climatic changes cause production costs to rise in Illinois, there is likely to be a corresponding decrease in total acreage planted on a given farm. Poorer quality land (less fertile, highly erosive) on any farm is likely to be taken out of production. Such action would tend to help hold the line on reductions of productivity per unit of land.

CHAPTER 6

POLICY IMPLICATIONS FOR EPA

I take as given that EPA is most concerned about implications of climatic change for managing environmental resources. Adjustments and adaptations to climatic change by Illinois farmers may raise some environmental concerns. Perhaps one way to target potential topics for further policy analysis is to identify those adjustments and adaptations which interact directly (either in a negative sense or a positive sense) with processes resulting in changes in environmental quality. Two such topics covered below are soil erosion and water quality.

Soil erosion. Soil erosion leads to two major types of environmental degradation. First, topsoils are transported off the farm leaving behind thinner soils. Second, soils that are transported off the farm can be deposited in places which cause environmental problems such as silting in of reservoirs and shipping channels and altered groundwater characteristics.

There are two climate change adjustment/adaptation strategies that may directly affect soil erosion. Increased tillage in fall, even if restricted to conservation tillage practices, will leave soils more susceptible to soil erosion during winter and early spring. This problem may be exacerbated somewhat by a warmer, wetter winter which leaves soils unfrozen and more exposed to water transport from runoff.

Reduction of planted acreage will result in less productive marginal lands being taken out of production. Marginal lands seem to be most susceptible to soil erosion. Thus, the fallowing of marginal lands could act to slow down rates of erosion. Moreover, such fallowing may serve to offset the negative effect of increased fall tillage on soil erosion. It is not clear what the net soil erosion outcome will be from increased tillage. However, there should be some inclusion of how climate change might affect tillage practices in the development of follow-on policies to soil conservation concerns such as T-by-2000.

Water quality. Adequate water quality is at risk from current agricultural practices in Illinois. Certain agricultural adjustment/adaptation strategies for coping with future climatic change, if such strategies are widely practiced, could worsen the situation. Such strategies deemed to be important in the possible degradation of water quality include increased irrigation and increased pesticide use. Another strategy, changes in nitrogen fertilizer application practices, is likely to affect water quality, but it is not certain whether effects will be positive or negative (more on this below).

If climate warming and drying is severe enough to warrant increased irrigation, then it can be concluded that surface water and groundwater supplies will be reduced to some extent. Some of this reduction would come from increased evaporation together with decreased precipitation. Withdrawal of water for irrigation from surface and groundwater sources would further reduce supplies.

Reduced water supply will certainly decrease water quality. With less total water supply, water which is left has less capacity to assimilate toxic substances. Effluents of any kind, agricultural or otherwise, will tend to be in higher concentrations in water bodies, all things being equal, if the amount of water in those bodies is reduced. Moreover, reduced water supply would probably lead to other problems like disrupted navigation of rivers, drying up of shallow wells, and reductions of water use to safe yield ratios for major urban water supply systems.

Pesticide residues in farm runoff lower water quality. If pesticide application rates were to increase in response to climatically induced pest population increases, then more pesticide residues will enter groundwater and surface watersheds. Once in a water system, pesticide residues can accumulate to levels that are toxic to aquatic life and to other animals that consume aquatic life, including humans.

Nitrogen-based fertilizers pose health risks to humans when they enter public water supply systems. In agricultural regions where nitrogen is applied to crops in large amounts, toxic nitrogen compounds have shown up in public water supply systems within those regions. At times, concentrations of nitrogen compounds have become great enough to force temporary closings of municipal water supply systems.

Climatic changes which bode well for corn production could provide incentive to increase fertilizer applications. The rationale behind such an increase has been discussed above. If more nitrogen fertilizers are applied to crops, there is likely to be more risk of contaminated public water supply systems in the regions where the nitrogen application is taking place.

Climatic changes leading to hotter and drier summer conditions will bode poorly for corn production. However, drier conditions than now would reduce nitrogen leaching from soils and into groundwater. Reduction of nitrogen loss in soils could lead to less nitrogen reapplication. A reduction of reapplication rates might also be helped by generally poorer yield expectations by farmers (discussed above). The net effect of a reduction of nitrogen application would be to lessen the amounts of toxic nitrogen compounds that enter public water supply systems to nontoxic levels.

The above issues of water quality changes as the result of climatically induced adjustments/adaptations on the farm are not well understood. Indeed, none of the potential environmental problems from adjusting and adapting to climate change that I have raised above may materialize. Nevertheless, the possibility of occurrence of these problems is sufficient to raise concerns. Perhaps the best way to manage the possible environmental effects of future climate adjustment/adaptation strategies at the farm level is to gather more facts about how farmers will make decisions in the face of climatic change. More sophisticated assessments are needed of the integrated climate-farm-market system. We cannot assess the potential environmental damages of future farming practices until we know how these practices will differ from today with or without climate change.

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CHANGING ANIMAL DISEASE PATTERNS INDUCED BY THE GREENHOUSE EFFECT

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FINDINGS[1]

The United States today produces about 20 million metric tons of red meat annually. This is almost twice the output of its nearest competitor, the Soviet Union (McCoy and Sarhan, 1988). In addition, dairy products, skins and hides, wool, and other animal products contribute to the value of production in the livestock sector.

About two-thirds of the agricultural land in the United States is devoted to grazing. Much of this land has no alternative food production use. In addition, livestock utilize enormous quantities of roughage and crop residues that would otherwise be wasted. The number of people employed in livestock production, processing, and marketing may total 10 million (McCoy and Sarhan, 1988).

Animal production tends to be in the western United States, close to the native forage of the plains and mountain states and to the land under cultivation in the mid and far west. Hog production is more concentrated, mostly in the north central states, than is that of cattle and sheep. More than three-quarters of the sheep are raised in the west, where plentiful feed sources are available.

Increased incidence of animal disease as a result of global climate warming due to the greenhouse effect has serious implications for the U.S. and world populations as a whole, but especially those directly involved in animal agriculture. Many animal diseases are kept in check largely because of the restrictions climate places on vectors, environmental habitats, and the disease-causing agents themselves (Blood et al., 1983; Gillespie and Timony, 1981; and Fraser, 1986).

Changes in animal health patterns can have important effects upon the quality of human life: economically, owing to increased price and decreased availability; nutritionally, through decreased consumption of animal products; physically, through changing zoonotic disease patterns; and socially, through the effects of disease states of companion and sport animals.

A detailed study is necessary to comprehend and elaborate the range of important changes that could result from climate changes induced by an accumulation of greenhouse gases.

Animal diseases that are likely to become increasingly important as the earth warms, due to the accumulation of greenhouse gases, fall into several categories: vector-borne diseases, zoonotic diseases, and foreign animal diseases.

The vector-borne diseases such as anaplasmosis, bluetongue, babesiosis, and Lyme disease may become increasingly important as larger areas of the United States are likely to become suitable habitats for the vectors of these and other diseases.

Zoonotic diseases such as Eastern equine encephalitis, intestinal nematodes such as canine hookworm and roundworms, Q fever, toxoplasmosis, and aflatoxicosis will probably also become more important as the environmental changes permit longer seasonality of these diseases and as their animal or environmental reservoir grows. Poultry diseases such as salmonellosis, coccidiosis, influenza, and New Castle disease may also be affected.

Foreign animal diseases, which even today pose an enormous threat to our animal industry, could become more important if movements of people and animals increase, taxing the control mechanisms that have been put into place by the USDA's Animal and Plant Health Inspection Services (APHIS). Diseases such as foot and mouth disease can spread through the action of wind and move across a region, infecting farm animals with lightning speed.

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Vector-borne foreign animal diseases including African swine fever and Rift Valley fever could have an even greater chance of becoming established, once introduced, because the habitats and sizes of vector populations might increase owing to the climate changes induced by the greenhouse effect. With greater numbers of vectors dispersed through larger geographic areas, the chances of introduction of a foreign animal disease into the American vector reservoir will increase proportionately.

Control of these and other arthropod-borne diseases will be increasingly difficult; as environmental temperatures increase, the generation time of these populations decreases, which has the effect of increasing the rate of arthropod evolution. Resistance to pesticides and possibly other control methods will evolve more rapidly, frustrating control efforts and making these diseases even more important economically.

Based on the epidemiology of the disease and the disease agent and vector biology, we chose four vector-borne diseases as examples of diseases whose distributions are likely to change owing to the greenhouse effect. Two of these diseases, anaplasmosis and bluetongue, are important diseases with wide distribution in the United States today. The remaining two, African swine fever and Rift Valley fever, although presently exotic to the United States, are likely to become more of a threat to American animal agriculture as climate changes induce an expansion of American vector habitats for these diseases and as movements of animals and people increase, precipitated in part by the predicted environmental and climate changes. As discussed on the preceding page, many other diseases will likely be affected. Detailed discussion of all of these diseases is beyond the scope of this preliminary study.

We draw the conclusions outlined below as a result of the literature search for the diseases that we have examined in depth and our firsthand experience with these diseases in the United States and throughout the world. Detailed discussions are presented in the specific sections for each disease.

Bluetongue As vector overwintering and year-around vector reproduction become possible in more states and the average lifespan of adult midges increases, we expect to see the geographical distribution of this disease expand northward and eastward. These predictions were made based on the known vector biology, nature of the bluetongue virus, and predicted climate changes as described by the GISS and GDFL models. These factors are described in detail in the bluetongue section of this report. The states in which bluetongue occurs in sporadic epizootics today might become endemic states for this disease as the climate warms. States that are now free from the disease could become areas that will experience occasional outbreaks (Figures 2 and 3). It is not very likely that the predicted climate changes will result in a significant vector habitat loss for the bluetongue vector. Bluetongue and its vector Culicoides currently are highly prevalent in some of the world's warmest and driest regions, including the African Sahel.

Anaplasmosis Likewise, as the temperature of northern states increases and, in particular, winters become milder than at present, and based on the known vector biology as presented in today's scientific literature, we predict that anaplasmosis might take on increasing importance as a disease of serious economic implications to U.S. animal agriculture (it is presently ranked second in animal diseases of economic importance) (Goodger et al., 1979).

Although the ticks that transmit anaplasmosis have feeding and reproductive habits largely based upon changes in day lengths, the tick numbers may well increase and their range may expand in northern states owing to less severe winter climates. In the south central states, where decreased precipitation and relative humidity levels are anticipated, it is possible that this disease could decrease in importance -- except where rangelands are, or become, a mixture of bushland and shrubs. The micro-environments surrounding bushes and small trees provide sufficient levels of relative humidity to keep these ticks from dying because of desiccation.

Furthermore, in the Midwest, if the climate warms and precipitation decreases, it is possible that crops such as corn will become less productive, resulting in the transformation of some of these marginal cropping areas to rangeland. This could make a disease such as anaplasmosis of greater importance in these areas.

Anaplasmosis is a disease that, once established in a herd, is clinically worse in adult animals. Stress, including that precipitated by high environmental temperatures, increases associated morbidity and mortality rates. Thus, the frequency of outbreaks of anaplasmosis and the resulting mortality and production losses will likely increase in the southern states, particularly during summer months as temperatures increase.

African Swine Fever As the temperature increases in the north-central and southeastern states, the tick carrier or vector for African swine fever could potentially extend its geographical habitat (Figures 6 and 7). If this disease is introduced into the United States, this increase in vector distribution and numbers would increase the risk of establishment of the disease. This is particularly important for African swine fever because it is thought that once this disease has become established in the soft tick vector population, it may be impossible to eradicate (Butler and Gibbs, 1984).

The chances that such a disease might be introduced into the United States will certainly be increased if geographical re-location of both human and animal populations occurs as a result of environmental changes that may be precipitated by the accumulation of greenhouse gases. This will necessitate increased efforts by the U.S.D.A.'s Animal and Plant Health Inspection Service (APHIS) to prevent the entry of African swine fever into the south.

Rift Valley Fever As with African swine fever, the greenhouse effect will have an impact on the possibility of introduction of this disease in two ways. First, if environmental change stimulates an increase in the movement and relocation of people and animals, there will be an increased risk of introduction of disease. This is particularly true for Rift Valley fever, because as a disease which affects humans, it is quite possible that human carriers of the virus could act as sources for introduction of the disease into our animal population.

Secondly, this disease is transmitted principally by mosquitoes, and at least three mosquito species widely distributed in the United States today are capable of doing so. Warmer temperatures, less severe winters, and precipitation increases all will contribute to increased mosquito populations and to an increase in the length of mosquito season in these areas. This increases the likelihood that once introduced, Rift Valley fever will become established in our animal populations. Although mosquito vectors capable of transmitting Rift Valley fever exist throughout the country, it is likely that this disease can become established only in the areas of the country where winter temperatures will be able to support active mosquito populations (Figures 4 and 5).

Objectives, Methods, and Report Presentation Format

The objectives of this preliminary study are as follows:

- Examine current literature on the greenhouse effect in light of the implications for changes in the patterns of animal disease in the United States;
- Undertake a literature review of four animal diseases that are either important or potentially significant in that their distribution and occurrence might undergo alterations due to climatic and environmental changes induced by the greenhouse effect;
- Examine the potential economic effects of these changes;
- Summarize the findings in a report presented to the Environmental Protection Agency; and
- Provide recommendations for further study.

This study was performed as a preliminary effort with the intention that it is likely to raise more questions than it answers. It is expected that this study will result in the allocation of sufficient resources to permit a detailed study of the effects of global warming on animal agriculture not only in the United States, but throughout the world. In the livestock industry as in other economic sectors, the effective links with world markets and the interdependency that is present today render the findings of a detailed study within the confines of a single country questionable. A thorough study should emphasize the United States but cannot ignore the changes likely to occur in livestock industries throughout the world.

The predictive findings presented in this report are based on an understanding of the diseases obtained through the literature search and personal experience with the diseases and are made according to the $2xCO_2$ regional values obtained with the GISS and GFDL models (Rind and Goldberg, 1988; Jenne, 1987).

This report begins with a summary section entitled Findings. Here important observations and conclusions are discussed. Additionally, the need for a more definitive study is pointed out.

The general changes which may be seen are presented and include a brief discussion of some of the potential changes that may be precipitated in the poultry industry. For the sake of brevity, we have concentrated this discussion on the confined chicken industry.

Next, four diseases are discussed that we feel represent the types of changing disease patterns that may be induced by the climate changes. We performed a detailed review of the recent literature on these diseases and have presented the important aspects of these diseases as they relate to climatic and environmental changes induced by the greenhouse effect. A discussion detailing the clinical signs, vector biology, epidemiology, economic importance, and means of control is included for each disease in addition to an economic analysis on the possible effects that changes in global climate may have on these diseases and their relative importance.

Two of these diseases, bluetongue and anaplasmosis, presently occur in the United States and are good examples of diseases that will probably become more important with the predicted climate changes. The other two diseases, Rift Valley fever and African swine fever, are foreign animal diseases that pose an everpresent risk of introduction into the Unites States. We believe that as the climate and environment change, not only will the risk of introduction of these diseases be increased because of shifts in human and animal populations, but the risk of these diseases becoming established and entering the vector reservoir will increase as vector populations and geographical distributions grow.

Economic Methodology

The economic methodology used for this study consists of estimating the impact of the spread of each animal disease on (1) decreased annual production resulting from the mortality associated with the disease, (2) decreased animal production resulting from the morbidity of the survivors of the disease, and (3) the decline in the value of the capital stock invested in animal herds because of the mortality associated with the disease.

Herd-specific mortality and morbidity rates were estimated separately for cattle and sheep, and for whether or not the animals are mature. These rates apply when the disease is first introduced on a large scale and would be reduced considerably once the disease becomes endemic. The rates used were based on reports in the literature and vary according to the disease and the its rate of spread when introduced into a new environment. Normally, it would take several years for these diseases to become established to these levels, and consequently the analysis is calculated to reflect the effects over a several-year period. Morbidity rates were adjusted to reflect the losses in production associated with infection. Both mortality and morbidity rates were applied on a state by state basis assuming the following percentage of herds to be infected within each state once the disease is endemic: Bluetongue 50%, Rift Valley Fever 20%.

To the losses from mortality and morbidity, as estimated on the basis of the cumulative decline in annual production as the disease spreads over a several-year period, is added the capital loss associated with the herd as a reproductive and growing out or fattening unit. The impact of the spread of the disease is estimated by aggregating the losses associated with that spread across the states in which the disease has become endemic. No losses are estimated for states in which there are only occasional outbreaks. Nor is any account taken of efforts to control the disease or of the costs of this control. The numbers, therefore, represent a worst-case scenario of what might happen if no control or containment measures were exercised.

The detailed tables involved in these calculations are presented in Annex A. Notes to those tables list sources and describe details concerning the calculations.

Methodology for Determining Predictions of Future Disease and Disease Vector Distributions

The distributions of future disease and disease vectors summarized in Figures 3, 5, and 7 were made based on a combination of current knowledge of the diseases and the vectors combined with the GISS and GFDL climate change scenarios as predicted for 2x levels of CO_2.

Current knowledge as presented in today's scientific literature is variable depending upon the disease and the vectors involved. Reasonably good data are available on the present distribution and vector biology of bluetongue, which permitted us to make projections that take into consideration the climate models, the vector biology, and the natural environmental resistance of the bluetongue virus. The literature on anaplasmosis, on the other hand, lacks details and specificity in terms of current distribution of both the vector and the disease in the United States. Consequently, no attempt was made to display either the present distribution of anaplasmosis or its vectors, and no attempt made to predict their potential future distribution. For Rift Valley fever and African swine fever, sufficient data in the literature on both the current distribution of the disease and the vector distribution and biology enable us to make general predictions on areas of the United States where these diseases could become established if introduced to America in the future.

Estimates of temperature and precipitation at $2xCO_2$ levels from the GISS and GFDL models were used in these disease projections. Monthly average mean temperatures from the GFDL model were used by region (southern Great Plains, Southeast, West Coast, and Great Lakes) for the months of January and July. The diurnal variations for these months and regions were then added and subtracted from these means to arrive at the high and low temperatures for the period. These values were then used to define the geographic limits of the vectors and/or disease agents according to the biology of the specific vector or disease-causing agent. The net change in precipitation predicted by these models was also taken into consideration.

The objective of the accompanying maps is to display to the reader the trends that we see possible. It is important to note that the inclusion or exclusion of a state in a group on any of the maps is at this time only speculative. There may be yet undescribed factors that are determinate in the distribution of a vector or disease in any of these states. Furthermore, the specificity of the climate data is not detailed enough to be able to determine, with any degree of certainty, changes between adjacent states. Finally, variation of disease distribution within states was not taken into consideration in this study. The inclusion of a vector or disease, in any given state, in the current or the projected maps is not meant to infer that the entire state is, or will be, affected.

General Changes Likely To Be Seen as a Result of Greenhouse Gas-Induced Global Climate Changes

As a result of global warming conditions, the meterological and environmental effects of the greenhouse effect are likely to induce changes on animal health patterns in three general ways. Changes can be anticipated in the habitats of insects that transmit animal disease, in floral environments, and in the patterns of animal and human movement. Each of these potentially could profoundly change the patterns of animal diseases.

Direct changes in environmental habitats will be precipitated as a result of the temperature and humidity changes induced by the accumulation of greenhouse gases. As the coastal regions experience increases in mean temperatures accompanied by precipitation increases, the habitats that can be exploited by various disease vectors will increase. Southern summers may become too hot for optimum tick activity in some areas; however, it is likely that activity will increase for ticks in these regions during spring and fall months. Many animal diseases are limited strictly by vector habitats (Fraser, 1986; El Shoura, 1987). As the environment changes, permitting an expansion of the vector habitat, the geographic distribution of a disease carried or spread by that vector is also likely to expand.

Vectors are living agents that carry disease organisms from one host to another. They are often arthropods that carry viruses, bacteria, or protozoans. There are two types of vectors: infected and mechanical. Infected vectors are ones in which the disease organism invades tissue and eventually multiplies itself within the vector's body. Infected vectors can often transmit the disease organism to their offspring. As a result, disease organisms can be maintained in vector populations for a number of generations. These vector populations can become reservoirs of infectious diseases. Mechanical vectors are ones that simply, by virtue of what sticks to a bug's feet or mouthparts, transport pathogens from one host to another.

Biological vectors become infected by the disease organism, but do so without showing any pathological reaction. In most cases, ingestion of the disease organism happens at feeding. The agent is carried to the gut along with the ingested blood, but instead of being digested it invades the cells lining the gut. Here, replication of the agent generally takes place before it spreads throughout the vector's body. Later the disease agent is disseminated to a new host, either through saliva injected when feeding or through waste or coxal fluids passed during or soon after feeding on the host.

For diseases occurring in a given region, incidence is frequently limited by the seasonal activity of vectors (Blood et al., 1983; Fraser, 1986; El Shoura, 1987). The vectors in the central and northern states do not undergo year-round activity owing to the temperature effects of winter, which halt or severely limit the reproductive cycles of the vectors, vector population, and animal-vector exposure, thereby reducing disease spread in these areas.

Based on an understanding of a disease, its epidemiology, vector biology, and current distribution, and on environmental changes that may occur according to the predictions produced at $2xCO_2$ values of the GISS and GFDL climate models, one can predict the future distribution of that disease. It appears that for some of the vector-borne diseases there may be an expansion of the present-day distribution northward, resulting in an increase in overall disease distribution. Unfortunately, the southern ranges of the diseases are likely to remain the same and, in fact, in many areas the diseases may become even more important. Despite excessively hot summers for some disease vectors, there may be an increase in fall, winter, and spring season vector activity, permitting the vector to undergo an increase in the number of reproductive cycles and a decrease in the generation time for each cycle, resulting in increased numbers and concentrations of vectors. This could result in an increase in the disease transmission rates and number of disease particles or units introduced into individual animals, provoking an increase in severity of these diseases.

The GISS and the GFDL models predict that the central areas of the great continental land masses, such as North America, will experience increases in temperatures and a decrease in relative humidity, causing a corresponding decrease in soil moisture. This will likely precipitate important environmental changes. In states where cereal and grain crops are marginally productive today, the importance of these crops to the state's agricultural industry is likely to decrease because of these decreases in precipitation and humidity. Nonirrigated land may dry to the point that it may be unable to sustain cereal cropping activities. These areas will take on increased importance as rangelands, permitting the expansion of extensive animal agriculture. The geographical distribution of the diseases may expand northward as the system of extensive range animal agriculture extends from regions of Texas, Oklahoma, New Mexico, and Arizona to the traditional breadbasket regions of the Midwest. Animal agriculture in the form of extensive rangelands is likely to remain important to the economies of the present-day southern range states, and the disease incidence in these areas could be expected to remain about the same. The seasonality of these diseases may change, with incidence increasing in the spring and fall, and decreasing during summer months owing to the effects of high temperatures and low humidity on the efficiency of vector reproductive and activity cycles. This increase in rangelands may also be enlarged as the American taste preference for beef continues to shift from the fat-laden meat of grain-fed feedlot animals to the leaner red meat produced by range animals reared under extensive range conditions.

Furthermore, in the Midwest as the environment dries and the predominant form of agriculture begins to shift away from crop-based systems to extensive animal agriculture, the ecosystems may undergo a change resulting in an increase in the distribution of bushes and shrubs. These are ideal habitats for ticks, as the humidity in the micro-environment surrounding the bushes and shrubs is considerably higher than the overall environmental average permitting tick survival and transmission of diseases such as anaplasmosis and babesiosis.

Also in the Midwest as subterranean water supplies permit, there may be an increase in irrigation for plant agriculture. If the importance of animal agriculture increases around these regions, the level of vector activity of such water-breeding insects as mosquitoes and midges may increase owing to the presence of standing water resulting from irrigation practices. This could be significant for diseases such as bluetongue, Eastern, Western, and Venezuelan encephalitis, and Rift Valley fever, should the latter disease be introduced to the United States.

Finally, as the effects of the climate changes become apparent on a worldwide basis, there could be large population shifts in both animal and human populations. This will result in the introduction of diseases and disease strains from one state to another, as the relative distributions of animal and human populations change. More important, however, will be the increased threat from animal diseases that are currently exotic to the United States. Among this group of diseases are several of the most important diseases known, including foot and mouth disease, rinderpest, hog cholera, and African swine fever. It is this group of diseases that poses the greatest threat to American agriculture. At least two of these diseases, foot and mouth disease and African swine fever, are capable of wind-borne spread, which can potentially make a small outbreak a major multi-state epidemic in a matter of a few days.

Compounding this risk is the speed and distances over which American livestock are presently transported. In a study of the animal shipment patterns from three major livestock markets of the Midwest during a seven-day period in the month of July, animals were transported to 42 different states (Figure 1) (Saulmon, 1969). If a foreign animal disease is introduced to one or more of the important livestock markets, it can spread to many of the contiguous 48 states in the space of a few days. It is important to keep in mind that the incubation period of rinderpest and foot and mouth can be long enough that a shipment of animals incubating the disease might possibly go unnoticed by all but the most alert animal inspectors at these markets. If introduced and spread in this fashion, a disease such as rinderpest or foot and mouth truly could be a disaster for the livestock industry, the effects of which would be felt throughout the American economy. In fact, foot and mouth disease has been introduced into the United States on eight occasions (McCauley et al., 1977). The most serious outbreak occurred in 1914, where the epidemic began in Michigan and spread to 22 states by 1915 following introduction into the Chicago stockyards.

Control of these diseases must be swift and extremely aggressive if the disease is to be eradicated from American soil, once introduced. Unless the disease spreads to the point of being extensively distributed, the control method of choice is total slaughter of all animals that potentially have been in contact with the disease. This, of course, is a very expensive undertaking, although far less expensive than permitting the disease to become established.

During the eradication program of the foot and mouth disease epidemic of 1914 - 1915, 172,000 cattle, sheep, goats, and swine were slaughtered (McCauley et al., 1977). If a worse case scenario is envisioned, and foot and mouth disease is introduced into the United States to the extent that to eradicate the disease 1% of the livestock population must be slaughtered, the costs of such a control program would be estimated at $539 million (1977 dollars). The net effect on consumer prices of meat could be up to $1.02 billion (McCauley et al., 1977).

The effect of the increased temperatures resulting from the greenhouse effect will likely have important economic ramifications for the poultry industry. Although today's chicken industry is a highly intensive form of animal agriculture with considerable attention given to environmental control in closed units, the effect of temperature increases on the industry could be considerable. Major investments may be necessary to cope with the increased temperatures that are expected in the central and southern states where much of our poultry

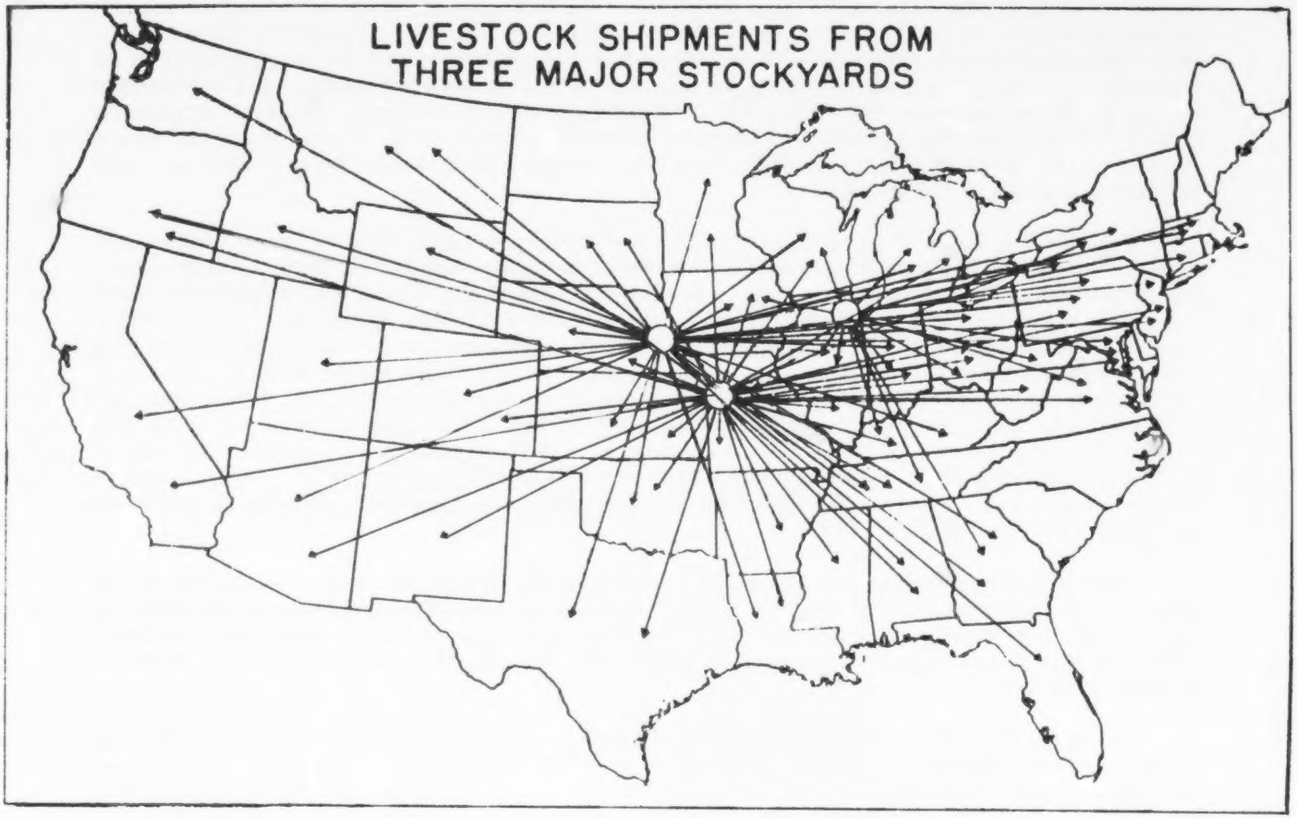

LIVESTOCK SHIPMENTS FROM
THREE MAJOR STOCKYARDS

Figure 1. Cattle movements during one week in July from Chicago, Omaha, and Kansas City (Saulmon 1969).

industry is concentrated. In many cases, cooling units and air quality control installations will have to be completely re-done in order to prevent heat stress and increased respiratory disease and related problems.

Salmonellosis, a stress-related disease, is likely to become more important. This carries significant public health implications in light of recent evidence of transmission of Salmonella enteritidis to chicken eggs before the egg shell is formed (St. Louis et al., 1988). These researchers estimate that egg-borne Salmonellosis in humans has been responsible for up to 70% of the cases of food poisoning in the northeastern United States in a two-year period from January 1985 to March 1987. The public health implications are clear if the prevalence of Salmonella enteritidis in chickens increases.

The recent extended heat wave of 1986 may be used as a good illustration of this problem. A drought occurred in the Southeast, which began in spring of that year. By July, average daily temperatures reached highs of 100°F or more. This put severe stress on the climate control systems of chicken houses from southern Pennsylvania through Georgia. At these temperatures, birds become reluctant to move even to reach nearby watering troughs resulting in dehydration, heat stress, and for many, death. By early July, some farmers in North Carolina were losing as many as 500 birds a day (Murphy, 1986). By the end of July when the heat wave broke, losses to the poultry industry in North Carolina were estimated to be $48.5 million, whereas losses of poultry in Georgia were estimated to be $5 million (United Press International, 1986). The temperatures experienced during this period are likely to be much more common when we have reached 2xCO_2 levels, according to GISS and GFDL models.

These changes could result in a slight northward expansion of the poultry industry, and depending upon the economics and availability of energy at the time, could result in a contraction of the southern margins of the poultry industry -- when and if the environment becomes too hot to permit the continuation of efficient poultry raising.

CHAPTER 1

BLUETONGUE

Introduction

Bluetongue is a viral disease that causes debilitating lesions of the mouth in a variety of wild and domestic ruminants. Several species of insects, in particular the biting midges (punkies and no-see-ums), act as insect vectors by transmitting the disease. Sheep manifest the worst clinical signs, but the disease is also significant in cattle and rarely so, in goats. Goats can, however, act as a reservoir. Clinical signs include erosions, hemorrhage, and edema of the mouth, tongue, and oral cavity. Frequently, there is a viscous mucopurulent nasal discharge that crusts on the muzzle; this is sometimes accompanied by diarrhea. Erosions are also common on the coronet band of the hoof causing acute lameness. Pregnant ewes and cows abort from the disease, and in some cases sheep will abort from modified live vaccines administered during gestation (Fraser, 1986). An infected fetus will show hydrencephaly (Gillespie and Timony, 1981).

In this country, the principal vector is Culicoides variipennis, one of the punkies that lives in and around farm wastewater. Bluetongue morbidity is highest in late summer and early fall and disappears with the onset of frost (Gillespie and Timony, 1981). This correlates to the biting activity of the vector. Increased incidence of the disease is seen when the warm season is wet (Gillespie and Timony, 1981).

Clinical Signs, Epidemiology, and Vector Biology of the Disease

Bluetongue was originally described as a clinical entity in South Africa in the early part of 20th century (Blood et al., 1983). It was first described in the United States in 1952 (Gillespie and Timony, 1[illegible]). In recent years, evidence of the disease has been demonstrated in a variety of geographic areas, and it is probable that the virus is moving into new regions (Metcalf et al., 1981).

Bluetongue may be approaching a cosmopolitan distribution. Incidence of the virus has been verified in most areas of Africa and extends along the Mediterranean coast of Asia and eastward through Pakistan and India. There have been unsubstantiated reports in Peru and recent confirmation of the virus in Australia (Della-Porta et al., 1981). In North America, only the United States officially reports outbreaks of the disease, although it is highly probable that it occurs in Mexico and Canada (Walton et al., 1984).

There are 20 immunological serotypes recognized worldwide (Gillespie and Timony, 1981), only a few of which occur in the United States (Gillespie and Timony, 1981). Virulence of the disease varies regionally and from outbreak to outbreak. In Africa clinical signs appear worse than those seen in the United States. These differences probably reflect the geographic and temporal distribution of particular serotypes (Gillespie and Timony, 1981).

Signs of the disease are similar in sheep and cattle, but severity and mortality are much greater in sheep (Gillespie and Timony, 1981). Mortality in sheep can approach 30% in this country (Fraser, 1986). Goats, although they can host the virus, rarely show clinical signs (Gillespie and Timony, 1981).

The most significant clinical signs are evidenced as erosions, hemorrhage, and edema of the mouth, tongue, and oral cavity. Often there is a viscous nasal discharge that crusts on the muzzle. Early in the course of the disease, affected animals show a high (105° - 107°F) temperature. There is commonly inflammation of the coronet band, and sometimes diarrhea. Pregnant ewes and cows frequently abort. An infected fetus will show hydrencephaly (Gillespie and Timony, 1981).

Morbidity is greatest in lambs that have recently lost colostral antibody protection or have been unexposed to the bluetongue virus during the period of passive antibody protection (Gillespie and Timony, 1981). In herds where the disease is endemic, older sheep are less severely and more infrequently affected. However, the resulting reproductive losses can be disastrous for sheep farmers.

Anderson (1970) shows serological evidence of bluetongue in 39% of dairy cattle and 48% of beef cattle (Anderson, 1970; Sellers, 1981). He also isolated virus from Culicoides spp. in Minnesota and concludes that bluetongue is more prevalent than previously thought and that, because the symptoms in cattle resemble bovine viral diarrhea, the disease is greatly underdiagnosed (Anderson, 1970; Sellers, 1981).

Clinical signs of bluetongue are variable and similarities exist with diseases such as foot and mouth disease, mycotic stomatitis, infectious bovine rhinotracheitis, bovine virus diarrhea, rinderpest, akabani disease, and vesicular stomatitis, making it difficult to readily identify the etiological cause in a particular outbreak (Gillespie and Timony, 1981). As a result, in areas where the disease has been previously unknown or infrequent, definitive diagnosis depends on extensive serological testing, viral isolation, or transmission studies. In areas where bluetongue is common, diagnosis of the disease is based upon clinical observation (Gillespie and Timony, 1981; Fraser, 1986). Elk, antelope, big horn sheep, Barbary sheep, moose, and several species of deer have all shown serological evidence of infection (Gillespie and Timony, 1981). This means that these wildlife species probably serve as reservoirs for the virus. Clinical signs and death have been induced experimentally in white-tailed deer (Callis, 1985).

Experiments show that the virus is only transmitted by insect vectors and that simple direct contact does not result in disease spread (Gillespie and Timony, 1981). As a result, distribution of the virus follows that of the vector, although there have been reports of outbreaks in areas where no known vectors occur.

Culicoides variipennis is most important vector for bluetongue in the U.S. (Wirth, 1979). It is a proven transmitter in the laboratory and there have been frequent isolations of the virus from midges of this species in nature (Wirth, 1979). While the distribution of the bluetongue virus is reliant on the Culicoides vector, the existence of reservoir populations is just as essential. Without reservoirs to maintain the virus between outbreaks of the disease, there would be no source for the Culicoides vector to acquire the infection. In the case of bluetongue, a definitive host is still unproven, but it is likely that one or several species of wild ruminants, domestic cattle, or goats host the virus from outbreak to outbreak without evidencing severe clinical symptoms. Its occurrence in sheep is probably accidental.

The prevalence of bluetongue in the United States was studied in the winter of 1977-78, when 19,758 blood samples from American cattle were examined for serological evidence of exposure to this disease. Overall, 18.9% of the samples were positive, with the highest rates of prevalence of the disease in the southwestern states and the lowest rates in the northern states. The highest rates of infection were in Puerto Rico and the Virgin Islands. High rates in the Southwest probably reflected a recent outbreak that occurred throughout that region (Metcalf et al., 1981). Generally, bluetongue epizootics have occurred in the southern regions of the United States where the climate is warmer and more favorable for the culicoides vectors (Figure 2).

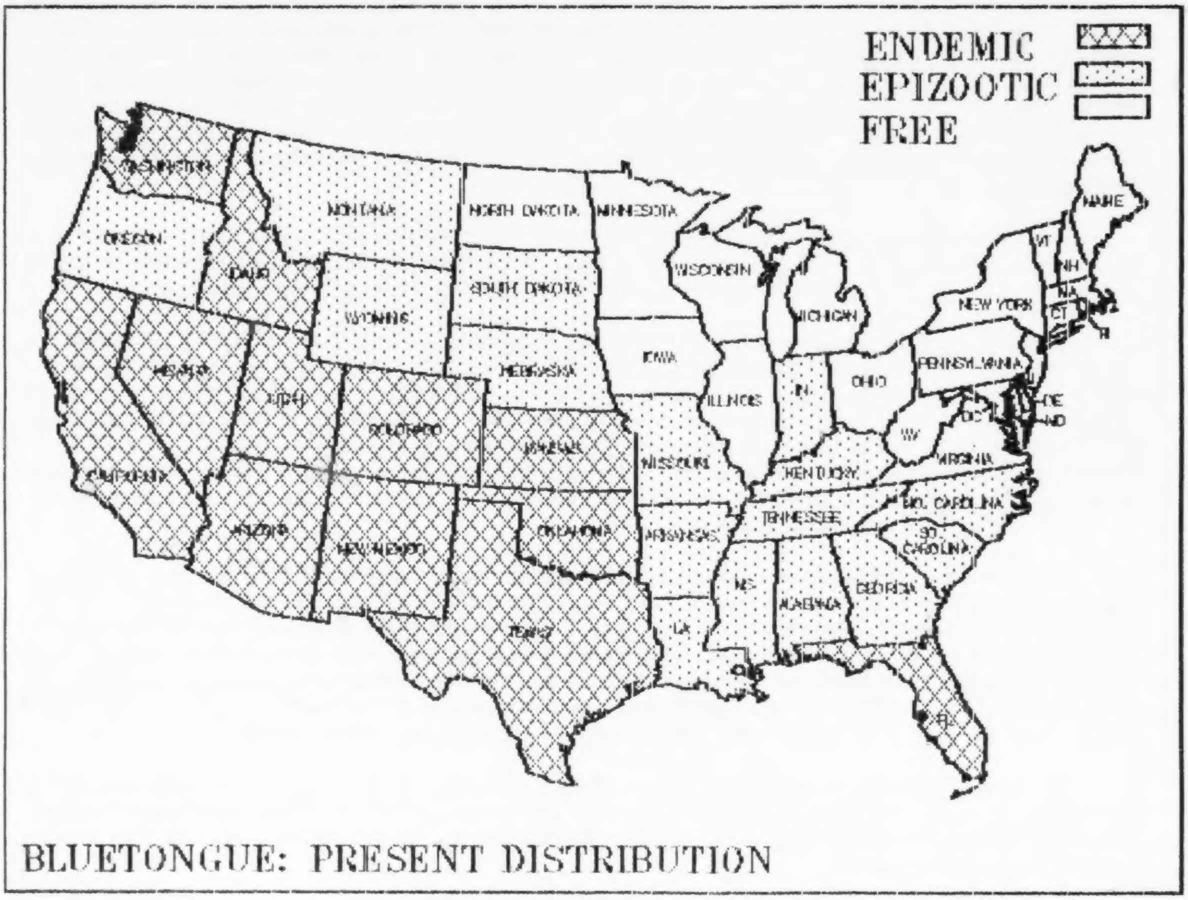
The insect carrier has been found to be an efficient transmitter of bluetongue. The organisms rapidly multiply in the midge. It has been estimated that by 20 days following a bite of a bluetongue-infected animal, one midge has the potential to infect three animals with sufficient numbers of the bluetongue virus to result in clinical disease (Sellers, 1981).

Economic Importance of Bluetongue

Bluetongue is of significant economic importance today in the United States, although accurate figures are very difficult to come by.

Control of Bluetongue

Control of the disease, whether in epizootic proportions or not, is probably best accomplished by a combination of vaccination programs and by minimizing contact between the vector and ruminant host.


ENDEMIC
EPIZOOTIC
FREE
WASHINGTON
OREGON
IDAHO
MONTANA
NORTH DAKOTA
MINNESOTA
WISCONSIN
MICHIGAN
SOUTH DAKOTA
WYOMING
NEVADA
UTAH
COLORADO
NEBRASKA
IOWA
ILLINOIS
IN
OHIO
PENNSYLVANIA
NEW YORK
MAINE
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WV
VIRGINIA
CALIFORNIA
KANSAS
MISSOURI
KENTUCKY
NO. CAROLINA
TENNESSEE
SO. CAROLINA
ARIZONA
NEW MEXICO
OKLAHOMA
ARKANSAS
MS
ALABAMA
GEORGIA
LA
TEXAS
FL
BLUETONGUE: PRESENT DISTRIBUTION

Figure 2. Present distribution of bluetongue (from Walton et al., 1984).

The vaccine against bluetongue is less than ideal, as pregnant animals should not be vaccinated because of a risk of abortion or teratogenicity. There have been reports of abortion following administration of modified live bluetongue vaccines to pregnant sheep (Fraser, 1986). Vaccination of sheep should take place after shearing because there is some evidence that the vaccine can cause wool breakage in animals showing severe reactions to the vaccine (Gillespie and Timony, 1981).

Minimizing contact between biting midges and animals includes decreasing vector populations in standing pools of water, increasing water runoff, and closeting susceptible animals during evening and nighttime hours when the vectors are active. However, the breeding habitats of Culicoides variipennis are discrete and not easily identified, but are highly productive, making control measures aimed at this vector difficult (Barnard and Jones, 1980).

Possible Effects of Global Climate Change on Bluetongue

Each generation of adult punkies is short lived, and it is this stage that is capable of transmitting the bluetongue virus to ruminants. There are a variety of immature stages (instars) that live in fresh/brackish water in the bottom sediments. Temperature in part determines the speed with which these instars pass from one stage to another. A shorter generation time potentially increases the number of reproductive cycles in any given season. Additionally, as described below, climate changes will also affect adult survivorship and the length of the active season for Culicoides.

The impact of a changing climate is manifested in altered patterns of water distribution. Here it is probable that the diseases would become more important in areas where there is an increase of standing pools of water, e.g. a partially flooded meadow down slope from herded cattle or sheep. Such an environment would be ideal for the increased propagation of Culicoides variipennis.

Introduction of bluetongue into a new geographic area has been blamed on strong surface winds blowing the midges on the wind. This was reported for the 1977 outbreak in Cyprus. The source of midges was interpreted to be Syria and eastern Turkey (Sellers et al., 1979a; Sellers et al., 1979b). Wind-borne introduction of bluetongue and Culicoides is potentially possible in states or regions that currently do not have the disease but that may develop into acceptable habitats as their environment changes.

Barnard and Jones (1980) report that seven generations of C. variipennis occur in Colorado each year. Generations happen between June and September and one overwintering generation develops slowly during favorable weather between October and March (Barnard and Jones, 1980). The predicted climate changes probably represent an opportunity for survival of greater numbers of adult and larval midges and more rapid development if the winters become warmer. Longer warm season periods would increase the season of biting activity for midges. A longer season of activity for midges would increase the number of animals exposed to midges by an increase in the length of the exposure period and by an increase in the vector population from an increased number of midge generations (Mullens and Rutz, 1984). Adult survivorship of Culicoides species is very important in the maintenance of the disease. There is evidence that bluetongue virus numbers peak in midges 10-14 days after ingestion of virus from an infected host (Foster and Jones, 1979). A warmer climate would therefore favor adult survivorship and increased disease transmission. Figure 2 divides the Unites States into areas where bluetongue is currently enzootic (occurring with a high degree of frequency and well established in the environment), epizootic (occurring infrequently in outbreak form when conditions for its propagation are ideal), and bluetongue-free areas. The principal factor preventing the establishment of the disease in the bluetongue-free states and the states where it occurs sporadically in outbreaks appears to be climate related (Walton et al., 1984).

Apparently there are two important factors that limit the distribution of this disease (Walton et al., 1984). First, bluetongue is established in areas where there is sufficient precipitation, standing water, and warm enough winters to permit over-wintering of the midge vectors to occur. Secondly, bluetongue virus reproduction is arrested in midges whose metabolic rate has been reduced below a critical level by environmental temperatures (Walton et al., 1984). Summertime temperatures of present-day Canada and the northeastern United States have temperatures that appear to be either too low or of too short duration to permit bluetongue virus replication (Walton et al., 1984; Metcalf and Luedke, 1980). As the winter temperatures warm in the northern Great Lake states, permitting establishment, maintenance, and proliferation of the midge populations and sufficient replication of the bluetongue virus within the midges, the states that are presently bluetongue free may become areas where outbreaks occasionally occur. The states that today experience occasional outbreaks could become enzootic areas for the disease as it becomes permanently established (Figure 3).

It is not likely that the predicted climate changes will result in a significant vector habitat loss for the bluetongue vector. Bluetongue and its vector Culicoides currently are highly prevalent in some of the world's warmest and driest regions. For example, Niger has an annual temperature mean greater than 80° and mean annual precipitation less than 15 inches, but has a bluetongue prevalence of more then 80% (Mariner et al., in press).

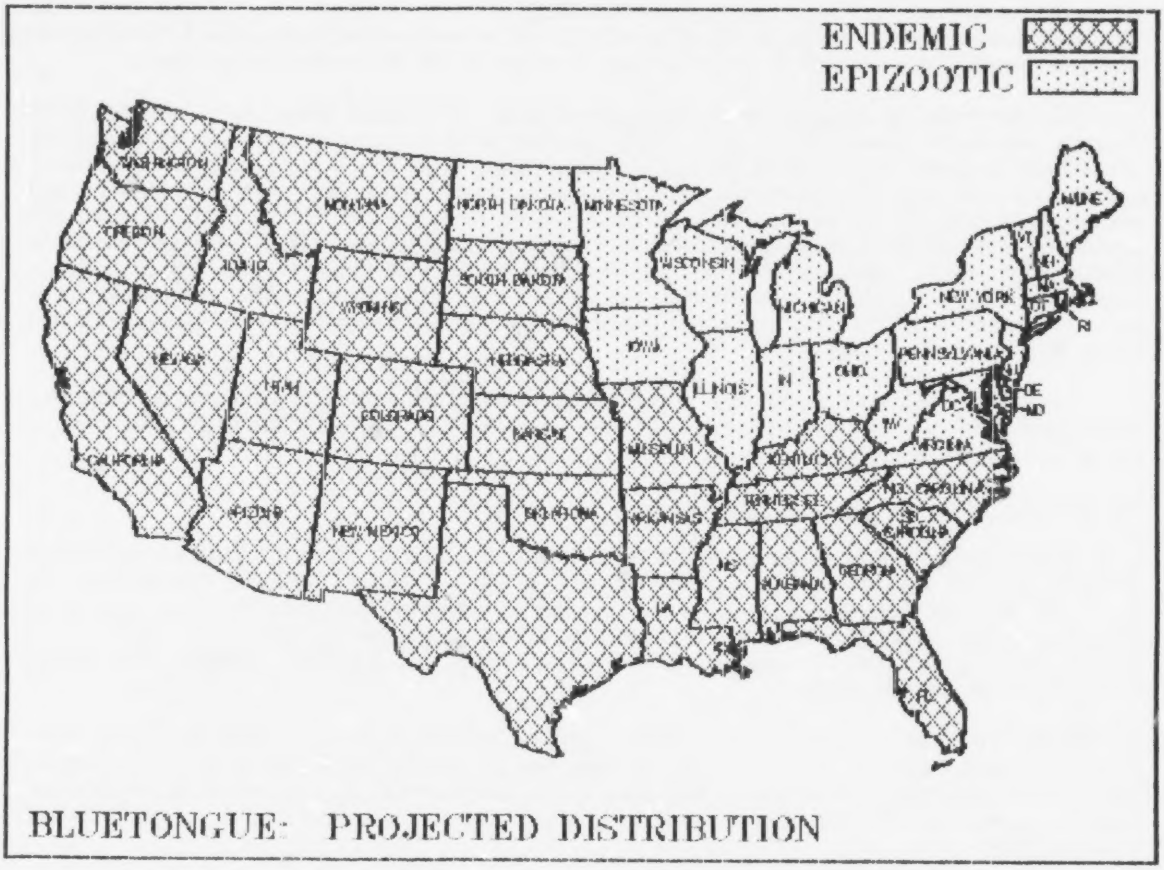
The changes predicted by the GISS and the GFDL climate models appear to be sufficient to permit these changes in bluetongue distribution to occur. These changes are likely to occur gradually and may not be apparent as cases of bluetongue are misdiagnosed as other similar-appearing diseases. This indicates a strong need for epidemiologic monitoring in these areas so that proper control and prevention measures may be initiated.

Economic Model of the Effects of Global Climate Changes on Bluetongue

Bluetongue disease is assumed in this analysis to become endemic in the states in which there are now only occasional outbreaks: Alabama, Arkansas, Georgia, Kentucky, Louisiana, Mississippi, Missouri, Montana, North Carolina, Oregon, South Carolina, South Dakota, Tennessee, and Wyoming.

Herd-specific mortality and morbidity rates were estimated separately for cattle and sheep and for whether or not the animals are mature. These rates apply when the disease is first introduced on a large scale and would be reduced considerably once the disease becomes endemic. Normally it would take several years for these diseases to become established to these levels, and consequently the analysis is calculated to reflect the effects over a several-year period. To the losses from mortality and morbidity, as estimated on the basis of the cumulative decline in annual production, is added the capital loss associated with the herd as a reproductive and growing out or fattening unit. The impact of the spread of the disease is estimated by aggregating the losses associated with that spread across the states in which the disease has become endemic. No losses are estimated for states in which there are only occasional outbreaks. Nor is any estimate made of efforts to control the disease or of the costs of this control. The numbers, therefore, represent a worst case scenario of what might happen if no control or containment measures were exercised.

Left uncontrolled, this would result in annual production losses associated with the disease equal to $634 million for cattle and $21 million for sheep, plus a decline in the value of the herd equal to $1287 million for cattle and $12 million for sheep. This totals 8% and 6% of the actual value of production in 1987 of cattle and sheep, respectively (models 1 and 2, Annex A).


ENDEMIC ▨
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OREGON
CALIFORNIA
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NEVADA
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NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
MINNESOTA
IOWA
MISSOURI
ARKANSAS
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WISCONSIN
ILLINOIS
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MICHIGAN
OHIO
KENTUCKY
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MAINE
BLUETONGUE: PROJECTED DISTRIBUTION

Figure 3. Projected future distribution (2xCO_2 levels) of bluetongue: projections are based on diurnal variations of mean temperatures for the months of January and July and mean precipitation predictions of GISS and GDFL climate models, present day disease distribution (Walton et al., 1984), and known vector and agent biology as presented in current literature. Projected presence in any given state does not imply statewide distribution due to localized environmental variability.

CHAPTER 2

ANAPLASMOSIS

Introduction

Anaplasmosis is a vector-borne rickettsial infection of cattle, sheep, goats, and wild ruminants including deer, big horn sheep, and elk. It is the second most important disease of cattle in the United States, with estimates of annual economic losses ranging from $36 to $100 million a year (Blood et al., 1983; Rebhun, 1984). The anaplasma organism is a parasite of red blood cells, and a corresponding major clinical feature of the disease is anemia. Losses are due to chronic debility, decreased growth and production, and death.

The distribution of anaplasmosis is nearly cosmopolitan, occurring in Africa, Asia, Australia, South America, and North America (Blood et al., 1983). Distribution of the causative rickettsial agent generally parallels the distribution of a variety of tick species, although its incidence does occur beyond the boundaries of known tick regions. Infection can be mechanically transmitted through biting flies, contaminated needles, and syringes, surgical equipment, and any blood to blood contact (Gillespie and Timony, 1981). Control and eradication of the disease is made more difficult by the common occurrence of a sub-clinical carrier state in infected adult animals. Precise distribution of anaplasmosis in the United States today is not known. This is a concern to the U.S.D.A., which is currently undertaking efforts to determine the distribution and severity of this disease. For this reason, we were not able to produce detailed current and projected distribution maps and economic projections for anaplasmosis.

Anaplasmosis is a significant disease not only because of its current economic impact but also because of the incipient nature of this disease. With the expansion of vector habitats, the disease has the potential for rapid spread and wide dissemination to new regions.

Clinical Signs, Epidemiology, and Vector Biology of Anaplasmosis

Clinical signs of Anaplasma marginale infection are difficult to discern. Infected animals frequently show no clinical signs for long periods of time, whereas others may die from chronic debility or even acute anemic crisis. Fever is the first clinical sign, but in range-fed or feedlot animals this often goes undetected. Furthermore, fever in anaplasmosis usually disappears before other symptoms become apparent (Gillespie and Timony, 1981). In fact, body temperature may be subnormal in the later stages of the disease (Gillespie and Timony, 1981; Blood et al., 1983).

Other clinical signs of anaplasmosis include depression, dullness, firm feces, icterus, peripheral lymph node enlargement, occasional edema, and less commonly, catarrhal enteritis as evidenced by mucus-tinged feces (Gillespie and Timony, 1981; Blood et al., 1983). As a disease, anaplasmosis is most important for adult animals under stress associated with high environmental temperatures, transport, change of feed, or calving (Jubb and Kennedy, 1970).

Diagnosis of anaplasmosis is best made by examining stained blood smears which show the rickettsia within the red blood cell. Usually, but by no means always, the anaplasma organism, which is contained within its own membrane, is seen pushed against the cell wall. Babesiosis, a similar tickborne disease, and other red blood cell parasites are also diagnosed in the same way by the specific morphology and placement of these inclusions.

Clinical anaplasmosis is primarily a disease of older animals. Young animals can be infected, and will remain infected (therefore are potential carriers if never treated) but may never show disease manifestations any time during their lives (Jubb and Kennedy, 1970). Instead, their bodies accept the infection and maintain a low level of circulating parasites that can seed rickettsia to the vector organisms. These vectors, usually ticks, can then pass the infection onto other susceptible animals. As a result, animals infected when they are young may not suffer clinical disease, but may serve as a source of infection for life as carriers. Additionally, these animals often fall into the category of "chronic poor doers" showing reduced production parameters and representing a significant economic drain.

If previously unexposed cattle are infected at the age of three years, they often become clinically ill, suffering from either a peracute or a chronic form of anaplasmosis. Those animals suffering from the peracute form may die within 2 to 3 days of the first clinical symptoms. Those affected chronically linger with weakness, icterus, and emaciation. In animals previously affected, clinical signs of the disease are often triggered in stress which can be demonstrated in the form of intercurrent disease, heat stress, or any physiological strain (Jubb and Kennedy, 1970). As previously mentioned, transport, feed changes, seasonal changes in climate, or calving are common stress-inducing factors that precipitate clinical anaplasmosis.

Losses from production factors and mortality due to anaplasmosis are worse during hot weather (Gillespie and Timony, 1981). Mortality may reach more than 50% depending upon the concurrent stress and if the disease is introduced into a herd or a group of susceptible individuals for the first time (Blood et al., 1983). Animals that survive will become carriers for an extended period of time (Gillespie and Timony, 1981). Additionally, these animals, unless a biological cure is effected, will detract from farm profits due to resulting production losses (Blood et al., 1983).

At least 20 species of ticks have been shown to experimentally transmit anaplasmosis (Blood et al., 1983). In addition, mechanical transmission has been documented by horseflies and mosquitoes (Kocan, 1986; Gillespie and Timony, 1981). Fortunately, only a few of these species of ticks are able to support a multiplication of the rickettsial organism within their bodies before passing it vertically to their offspring, which can then be the source of transmission to other animals. In the United States, the most important of these biological vectors are the ticks _Boophilus annulatus_, _Dermacentor occidentalis_, _Dermacentor andersoni_ (Gillespie and Timony, 1981). The significance of these species is that the anaplasma organism can persist by reproducing within the tick-wildlife population indefinitely without contact with the domestic farm animals. This makes the eradication of anaplasmosis very difficult, if not impossible, once is has become established within a given ecosystem.

Development of the rickettsial organism within the tick starts with infection of the tick gut cells after feeding on an infected animal. Several developmental stages follow and to some extent parallel developmental stages of the tick. Eventually, the tick hemocyte (equivalent to a mammalian white blood cell) becomes infected. Finally, the tick's salivary glands become infected and the organism is then transmitted to the tick's host during the next blood meal. Surprisingly, anaplasma is not transmitted to the host rapidly, as tick attachment to the host must approach 6 days before the rickettsial infection is transmitted (Kocan, 1986). As discussed below, this has important implications for the control of the disease in domestic animals.

Economic Importance of Anaplasmosis

Anaplasmosis is said to be the second most important disease of cattle in the United States (Goodger et al., 1979). Estimates of losses vary from $35 to 100 million per year (Rebhun, 1984; Blood et al., 1983). Nevertheless, there is a scarcity of information on the geographic distribution, prevalence, and economic effects of this disease.

Control of Anaplasmosis

The primary problem in control of anaplasmosis is keeping adult uninfected animals out of endemic areas, and keeping infected carrier animals out of nonendemic areas. The extensive nature and rapidity of livestock transport in present-day America makes this difficult (Jubb and Kennedy, 1970; Saulmon, 1969). Likewise, if cattle from a distant place move into an endemic area where the disease is subclinical, these older cattle can become rapidly infected.

Fortunately, there are effective treatments for anaplasmosis. The carrier state can be effectively eliminated from animals through the application of one of the following antibiotic protocols: (1) injection of 5 mg/lb oxytetracycline, daily for 12-14 days; (2) injection of 15 mg/lb aureomycin, daily for 16 days; or (3) injection of 5 mg/lb tetracycline for 10 days (Fraser, 1986; Howard, 1986; Blood et al., 1983).

Clinical anaplasmosis may also be treated by tetracyclines. Imidocarb, a newer drug, causes rapid clearance of the anaplasma bodies from red blood cells of clinically ill animals at a dosage rate of 5 mg/kg given every 14 days for two to three cycles (Howard, 1986; Blood et al., 1983; Fraser, 1986).

Since it is thought that a tick must feed on an animal for up to 6 days before seeding the host animal with enough anaplasma bodies to be infective, a good tick control program can be an effective means of prevention (Kocan, 1986).

All of the above-described control systems are economically expensive (Gillespie and Timony, 1981).

Vaccinations against anaplasmosis have been successfully produced, but they are not used extensively in the United States owing to the presence of the vaccine-induced antibodies, which cannot be detected from antibodies produced as a result of natural disease. Thus, there is no way to differentiate between vaccinated animals and those naturally infected. This becomes economically significant for interstate or international animal transport. Few purchasers or regulatory bodies will risk the potentially disastrous results by importing vaccinated cattle.

Both inactivated and attenuated vaccines have been developed. They appear to be effective which makes "global" or wide area vaccination enticing. However, such extensive vaccination of all susceptible animals for the disease would be a very expensive undertaking, and one would be unable to eliminate the disease entirely owing to the wild animal reservoir. Furthermore, it is highly unlikely that an effective vaccination program could be mounted in enough countries to permit international trade to proceed unhampered, and if this were not the case, most countries would not accept the risk of vaccination of their animals, which would render them indistinguishable from those that are clinically infected.

Possible Effects of Global Climate Change on Anaplasmosis

There are several striking features about the disease that make it a concern in a warming climate. These factors combine to make an already extremely important cattle disease in the United States even more serious. First, the day to day activity of the vector insects will probably increase, causing a rise in vector-host contact and an increase in the transmission of the disease. The exception to this might be in the southern central states where, according to the GISS and GFDL climate models, summertime temperatures will increase and relative humidity will decrease. This may result in a decrease in the vector activities during these periods. Depending upon the photoperiod response characteristics of individual tick species, however, there may be an increase in the vector activities in either the spring or fall in this region. Second, the distribution of the habitat conducive to the vector may expand. This will be due largely to the increased warming in the northern states, in particular the Great Lake states.

The added stress of increased temperatures is likely to precipitate clinical anaplasmosis. Furthermore, losses from anaplasmosis are more severe during hot weather and in warmer climates (Gillespie and Timony, 1981). Changing vector distribution will cause anaplasmosis to creep into areas where there are populations of susceptible adults and juvenile cattle.

In cattle-producing systems, carrier animals, which can be impossible to identify without the collection of blood samples followed by laboratory testing for antibodies, are a reservoir for introducing the anaplasma infection to previously unexposed animals. With rapid and frequent transport of animals from one part of the country to another, the problem becomes worse because if infected animals move into new territory where the infection has not previously been encountered, the carrier animal becomes a source of infection through arthropod vectors to other animals. The resulting losses from outbreaks of anaplasmosis can be disastrous. This is especially true as the clinical signs of anaplasmosis are not particularly specific for this disease, complicating and often delaying diagnosis.

CHAPTER 3

RIFT VALLEY FEVER

Introduction

Rift Valley fever is a vectorborne viral disease of sheep and cattle characterized by explosive outbreaks, symptoms of severe liver disease, abortion, and frequent rapid death.

Although its worst impact is on sheep and cattle, it also affects humans, camels, monkeys, mice, rats, ferrets, hamsters, and goats (Blood et al., 1983). Previously limited to Africa, Rift Valley fever has recently spread to the Asian continent in the Sinai peninsula (Hoogstraal et al., 1979; Blood et al., 1983; Gillespie and Timony, 1981). Spread to other areas of the world is a prominent and potential problem.

Whenever outbreaks are seen in animals, there is frequently concurrent morbidity in humans (Gillespie and Timony, 1981). As a result, incidence of the disease has important public health implications (Gillespie and Timony, 1981). In humans, symptoms resemble influenza with occasional cases complicated by long-term eye problems and more rarely death (Blood et al., 1983).

Clinical Signs, Epidemiology, and Vector Biology of Rift Valley Fever

In domestic animals, sheep are most seriously affected, cattle are less affected, and goats rarely exhibit serious signs. Morbidity and mortality percentages are generally higher for young animals than for adults.

Young lambs suffer 95-100% mortality (Gillespie and Timony, 1981); and young calves can show 70% mortality (Blood et al., 1983; Gillespie and Timony, 1981). Death in these animals is often seen within 72 hours of the start of incubation. The rapid evolution of the disease process affords little time for treatment.

Pregnant ewes with Rift Valley fever usually abort, and mortality in sheep is often 20-30%. Mortality may be characterized by peracute death with no clinical signs, or death may follow a display of a variety of signs including vomiting, purulent nasal discharge, or hemorrhagic diarrhea (Gillespie and Timony, 1981). Signs in adult cattle mimic those of sheep except that death ensues in only about 10% of the cases. Losses in any case, whether death or debility, are severe.

In humans, the disease manifests with signs similar to influenza (headache, muscular pain, fever), although there can be short- and long-term degeneration of the retina with resulting loss of vision (Schrine, 1951; Freed, 1951; Ayoub et al., 1978).

Rift Valley fever is caused by a single stranded RNA virus in the Bunyaviridae family (Gillespie and Timony, 1981). The virus is classified technically as an arbovirus since its principal mode of transmission is through infection of insect vectors (Blood et al., 1983). Although the disease was first described in Kenya in 1931, it is probable that this disease had previously occurred for years (Gillespie and Timony, 1981). The recent history of the disease shows a virus with variation that may be becoming more virulent and biologically broader in its adaptability to new ecological settings (Walsh, 1988).

Rift Valley fever had been a stable endemic disease of the Rift Valley in eastern Africa for a number of years (Kaschula, 1956). In the last twenty-five years, the virus appears to be actively moving into new geographic areas, new ecosystems, and new animal populations (Kaschula, 1956).

A large epizootic occurred in 1951 in South Africa when 100,000 sheep and cattle died. About 20,000 people were infected but no deaths were reported (Simpson, 1978). There was also another epizootic in South Africa in 1974-75, in which human fatalities were reported (Simpson, 1978). Another epizootic broke in Egypt in 1977 just northwest of Cairo. Over 200,000 people were infected, with approximately 600 deaths occurring (Miller, 1980; Walsh, 1988). The fact that this epizootic continued throughout two years suggests an over-wintering mechanism for the virus. It is possible that the virus maintains itself in the vector populations either in individual insects that survive the winter or by transovarial passage to insect offspring (Hoogstaal et al., 1979). One study reports that the virus is not maintained for any length of time in mosquito populations. It is also quite possible that the virus survives in an unknown vertebrate host, which reinfects vector populations when they take a blood meal in the spring or when the next epizootic begins (McIntosh et al., 1980).

As a clinical entity, Rift Valley fever, to this point in time, occurs only on the continent of Africa, although recent serological investigation shows evidence of the virus in man and animals in Asia on the Sinai Peninsula just east of the Nile River. This in itself is unremarkable because the distance traveled from the 1977-78 epizootic is small (Miller, 1980). However, the event along with the 1977-78 outbreak signifies movement of the virus into a new ecological setting and technically onto a new continent (Hoogstraal et al., 1979).

More recently, in 1987-88 there has been an outbreak of Rift Valley fever in West Africa involving the countries of Mauritania, Senegal, Gambia, and Mali (Walsh, 1988). Like other recent outbreaks, this one has affected man and domestic animals causing significant mortalities (Walsh, 1988). The Pasteur Institute of Dakar estimated the total number of human cases of Rift Valley fever in Mauritania at 1264 with 224 known deaths (Walsh, 1988). Serological evidence for Rift Valley fever has been reported in several other west African countries including Cameroon, Nigeria, and more recently Niger (Mariner et al., in press; Walsh, 1988; Ezeifeka, 1982; Fagbami, 1973). In the pastoral zone of Niger, a 1988 survey revealed over a 40% prevalence rate among camels in the region (Mariner, 1988).

Rift Valley fever seems to have outbreaks on a 5-7 year cycle, some more severe than others. Incursion into domestic animals seems accidental and appears only when conditions are right; that is, when there are high numbers of both vectors and susceptible animals, infection of domestic animals results when the virus particles are transferred to the blood. The carrier of the virus can be arthropod or mechanical; reused needles or surgical equipment can serve as mechanical carriers. Likewise, bloodsucking insects can also be mechanical carriers, but in addition some insect species can become infected and can serve as biological vectors. Spread of the disease by vector is more efficient than mechanical spread since the vector organism can serve as a persistent source of virus particles, whereas a mechanical carrier exhausts its supply of virus particles with time and activity.

In animal populations, insect vectors are the principal means of introducing Rift Valley fever virus, mosquitoes being the worst offenders. In humans, close contact with infected animals frequently induces the disease. It seems that in the latter case, contact with blood products, especially in persons with skin abrasions, may be the infective route (Blood et al., 1983), although inhalation of blood products in abattoirs has also been suspect (Miller, 1980).

As many as 26 species of arthropods may act as vectors for the Rift Valley fever virus on the African continent (Miller, 1980). Most of these species are mechanical carriers, although there are several very efficient biological vectors in the group. Such biological latitude ensures successful transmission and survival of the virus in a variety of ecological settings, which poses significant problems for disease control.

Several species of mosquitoes indigenous to Africa that carry Rift Valley fever are also found in the United States. It is also possible that the virus could also be successfully carried by arthropods native to only North America.

One study in Africa attributes the mosquitoes *Culex theileri*, *Culex univattatus*, *Aedes juppi*, and *Aedes lineotopennis* as the most efficient vectors (McIntosh et al., 1980). *Culex theileri* is thought to be biggest offender, especially on the plateau areas of central Africa (Hoogstraal et al., 1979). It feeds on man, cattle, sheep, and other animals. It is also long-lived, from early summer to mid-winter, and occurs in great numbers. Other investigators have attributed the worst offender status to *Culex pipiens* citing that the 1977-78 epizootic in Egypt was probably maintained by *Culex pipiens* (Hoogstraal et al., 1979; Miller, 1980)

Of the vectors shown to transmit Rift Valley fever, three species of mosquitoes appear in the United States: Culex pipiens, Aedes aegypti, and Aedes taenierhynchus. Their existence in the United States would provide a viable mechanism for disease spread if the virus were to become established here.

Aedes taenierhynchus has a widespread distribution ranging from California to Peru and from Massachusetts to Brazil along coastal areas and inland salt waterways (Stone et al., 1983).

Aedes aegypti in the subgenus Stegomyia is a pantropical species with the highest incidence reported to be in Egypt. Two subspecies have been reported in Georgia: Aedes aegypti taeniatus, and Aedes aegypti excitans (Stone et al., 1983).

Aedes aegypti is reported to transmit Rift Valley fever in experimental trials (Turrell and Bailey, 1987). However, it has not yet been found to carry Rift Valley fever in nature (Turrell and Bailey, 1987). It is also shown to be an inefficient vector (Turrell and Bailey, 1987).

Distribution of Culex pipiens is worldwide within 60°N latitude and 40°S latitude (Horsfall, 1955). It can, in places, extend northward to the Arctic Circle as in Norway (Horsfall, 1955).

It has also been found that with decreasing feeding efficiency there is an increase in virus dissemination on the part of the vectors. In other words, the more contacts a vector insect has with a mammalian host, the greater the incidence of disease transmission (Turrell and Bailey, 1987). This has important ramifications for the spread of the disease during an outbreak, as one vector can potentially infect many host animals or people.

Economic Importance of Rift Valley Fever

The economic importance of Rift Valley fever has to date not received attention in the literature. In the recent outbreaks in Egypt and Mauritania, Senegal, Mali, and Gambia, it is clear that the economic effects have been significant in terms of animal mortality, animal production losses, human mortality, and human morbidity.

Control of Rift Valley Fever

A human vaccine against Rift Valley fever has been developed and is currently being tested by the U.S. Army. An animal vaccine under development soon will be tested in west Africa.

Currently, most control methods are aimed at mosquito control. In a study done on time of mosquito activity, it was found that Culex pipiens had greatest flight activity after 12 p.m. (midnight). This time would then be the best time for insecticide administration (Mitchell, 1982). Most control efforts to date have been largely directed toward control of mosquito breeding grounds.

Possible Effects of Global Climate Change on Rift Valley Fever

The potential for spread of Rift Valley fever from Africa to other regions is great. It has already made great progress across the African Continent with some evidence of its occurrence along the Mediterranean Sinai. One theory on the route of spread from East Africa to Egypt, western North Africa including the Maghreb, and down to West Africa involves the trans-Saharan camel caravan trade routes. Human travel is perhaps the greatest threat in the spread of Rift Valley fever worldwide. People appear to be quite capable of acting as carriers and that, in conjunction with the diseases's apparent ability to "infect" a wide variety of arthropod vectors, make this disease a conceivable threat worldwide. The impact of a changing climate can only exacerbate the problem. Mild winters, longer summers, and increased precipitation in coastal areas will contribute to increased vector populations and seasons, for much of the United States. This will serve to increase the risk of this disease becoming established in the environment if introduced.

The shorter the generation time for any population, the more effective the population usually is as a vector, transmitting pathogens to domestic and wild animals. The short generation time of the mosquito permits rapid colonization and facilitates expansion into new areas. Optimum temperature for development is around 25°C (Horsfall, 1955). At approximately 35°C development halts (Horsfall, 1955).

Several unanswered questions require further study. Rift Valley fever seems to be a disease on the move. In the last half century, the geographic range of the disease has extended across the African continent even into such geographically isolated ecological territories as South Africa, the Rift Valley in East Africa, and northern Egypt. The virus has been able to successfully infect a variety of vectors in these geographic areas. Presently, there is a real concern for eventual worldwide distribution.

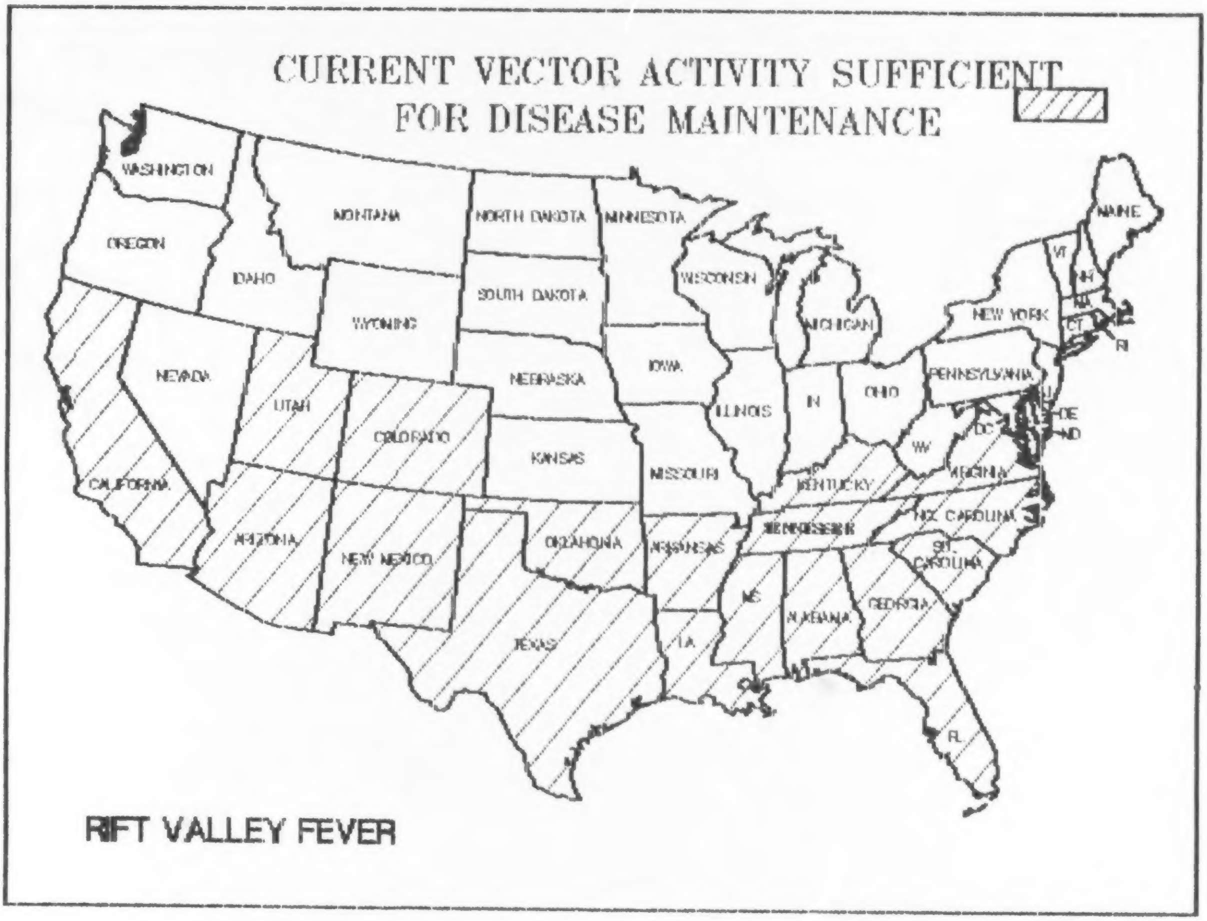
Some concern exists that humans may be a suitable carrier host for the virus into other parts of the world. It is still not clear if humans, camels, or other yet unknown hosts were responsible for the spread of Rift Valley fever into North Africa from East Africa. Apparently, humans become viremic (carriers of virus particles in their blood); this has important ramifications concerning the spread of this disease (Miller, 1980). A possible scenario is that if someone in an endemic area at the outset of an epizootic was bitten, and traveled to another country while in the incubation period, he could introduce the virus in local indigenous vector arthropods and eventually to domestic and wild animals, and to other humans. There is, therefore, real concern that humans could act as carriers to biting arthropods (Miller, 1980).

The impact of a changing climate, especially a warming one, would be that if the virus was in the vector population during a time when there was a great increase in vector numbers, as could be expected along the costal areas that are expected to warm considerably and remain humid, the spread of the disease would be very rapid. Culex pipiens, and Aedes aegypti and Aedes taenierhynchus all are more successful in areas of increased rainfall and stagnant, and polluted waters. Aedes taenierhynchus likes to live along coastal areas where there may be a significant rise in sea level (Horsfall, 1955).

Extended cold weather, 2°C or less is detrimental to larval development and growth. Incubation optimum temperature lies between 21°C and 30.5°C (Horsfall, 1955). Development throughout the mosquito lifespan is best in the 25°-30°C temperature span. Extreme cold, 3°C or less, is detrimental to the development of Culex pipiens (Horsfall, 1955). Therefore, the expected global warming would not only open up new vector habitats but also increase the rate of vector development and extend the season of vector activity. At temperatures above 25°C, mosquitoes tend to seek out cooler areas, and at temperatures above 30°C, their activity is generally diminished.

Over-wintering of Culex adults is generally in protected areas, although some adults even can survive temperatures well below freezing (Horsfall, 1955). It is clear that as the climate warms, over-wintering will become an important factor in increasing vector population sizes.

Although the complete epidemiological picture of Rift Valley fever is not yet clear, and capable vectors are known to exist throughout the United States, the disease is more likely to become established in regions that are sufficiently warm and moist to sustain reproductive and feeding activity on a year-round basis. States where mosquito activity may be sufficient to permit the maintenance of Rift Valley fever in the host-vector cycles are shown in Figure 4. It is important to emphasize that Rift Valley fever has never been introduced into the United States. These states were grouped according to the known vector biology of the mosquitoes that are proven vectors for this disease. It is possible that other, yet unidentified factors may well prevent the establishment of the disease in these states. Furthermore, environmental variability within any one state may preclude establishment of the disease in certain areas. Figure 5 demonstrates the hypothetical expansion of areas that may be able to support sufficient mosquito vector activity to permit establishment of a reservoir of Rift Valley fever, should it be introduced into any of these states. This figure incorporates the environmental changes at $2xCO_2$ levels as predicted by the GISS and GFDL climate models. The exact distribution of mosquito populations able to support this disease is beyond both the present knowledge as presented in current literature and the scope of this study. The important point is that there are areas of the United States that could potentially support this disease, and these are likely to expand with the environmental changes predicted by these climate models.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MICHIGAN
SOUTH DAKOTA
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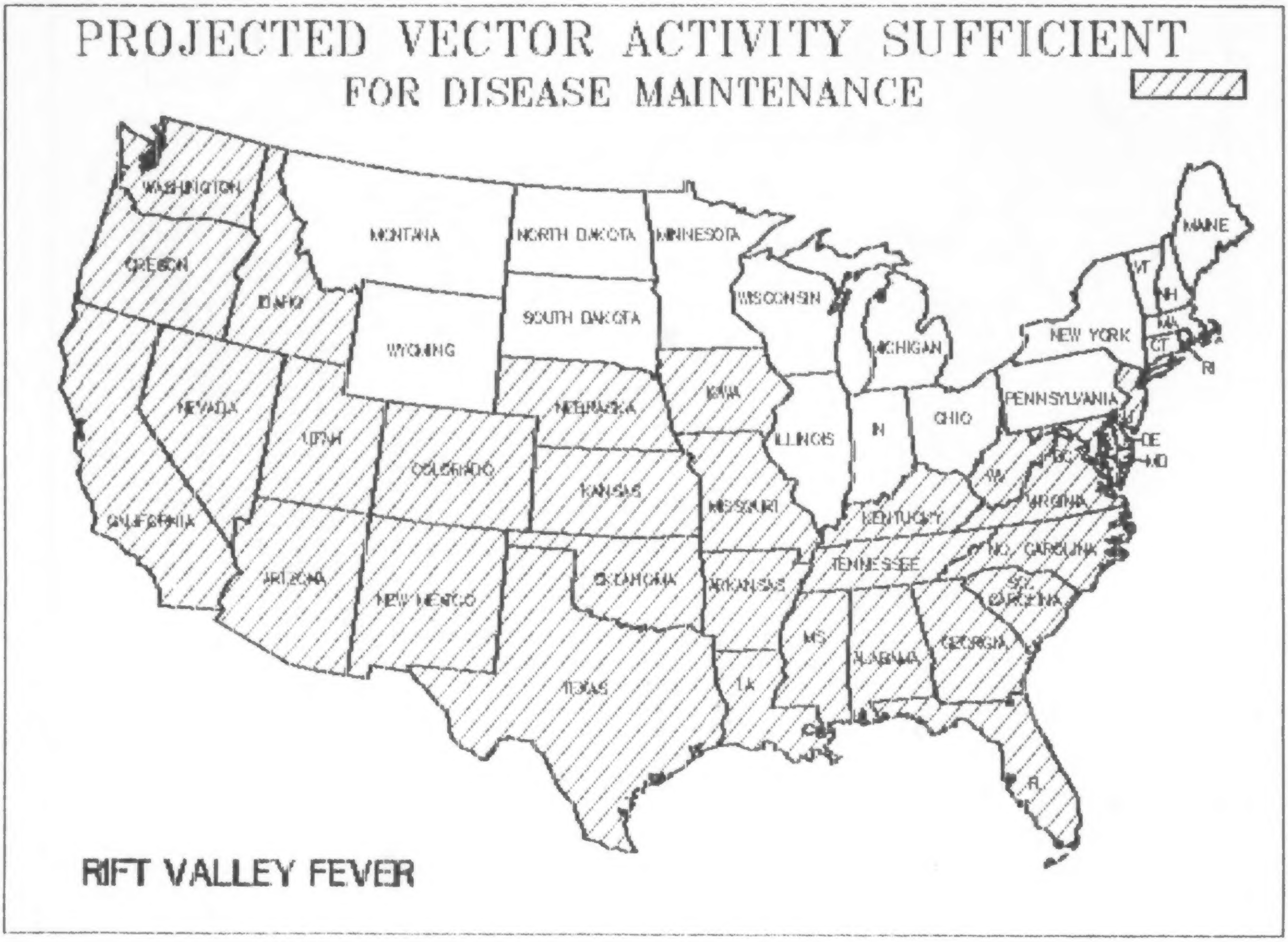
NO. CAROLINA
SO. CAROLINA
TEXAS
LA
MS
ALABAMA
GEORGIA
FL
RIFT VALLEY FEVER

Figure 4. States where present day mosquito activity may be sufficient to permit the establishment and maintenance of Rift Valley fever: assumptions are based on present day diurnal variations of mean temperatures for the months of January and July and mean precipitation as described in the GISS and GDFL climate models, and known vector and agent biology as presented in current literature. Rift Valley fever does not currently occur in the United States. If introduced through entry of infected people or animals, the shaded states are those where this disease is more likely to become established owing to the current vector activity.


PROJECTED VECTOR ACTIVITY SUFFICIENT
FOR DISEASE MAINTENANCE
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RIFT VALLEY FEVER

Figure 5. States where future (2xCO$_2$ levels) mosquito activity may be sufficient to permit the establishment and maintenance of Rift Valley fever: projections are based on diurnal variations of mean temperatures for the months of January and July and mean precipitation predictions of GISS and GDFL climate models, and known vector and agent biology as presented in current literature. Rift Valley fever does not currently occur in the United States. If introduced through entry of infected people or animals, the shaded states are those where this disease is more likely to become established owing to the potential vector activity.

Culex pipiens is a nonmigratory species, although they have been recorded to travel on wing a distance of 5 kilometers (Horsfall, 1955).

Wind velocities above 16 km/hr curtail mosquito flights. Flight activity increases as temperatures rise to 25°. Above this, flight activity is correlated to humidity, not to temperature (Horsfall, 1955).

The distribution and success of any populations of mosquitoes, is inextricably interlocked with climate and the dynamics of day to day variations in weather and environment. For instance, predation on the larvae of Aedes taenierhynchus is limited by frequent rainfall. Flooding into new flat water pools is not deep enough for Gambusia puncticulata, Lima caymanensis, and Rivulus marmoratus minnows. These pools are sufficiently deep for Aedes taenierhynchus to live and develop in, and development of the larval forms is done early in the flooding of new areas. Drier wet seasons are sometimes more favorable for the mosquitoes, for there are not great increases in the Gambusia populations concurrent with the increases in the mosquito population. Deeper water disperses Gambusia into such wide areas they are unable to feed effectively on the developing mosquitoes at the beginning of the wet season, when there are few Gambusia about. This is the time when most mosquito larvae are developing (Todd and Giglioli, 1983).

Economic Model of the Effects of Global Climate Changes on Rift Valley Fever

Rift Valley fever is not currently found in the United States. It could, however, be introduced and become established in several states. The analysis was undertaken for two of these: California and Florida. Based upon mortality rates of 2% for cattle and 14% for calves and morbidity rates of 8% herd-specific mortality and morbidity rates were estimated separately for calves and cattle (Blood et al., 1981; Howard, 1986; Gillespie and Timony, 1981) These rates apply when the disease is first introduced on a large scale and would be reduced considerably once the disease becomes endemic. Normally it would take several years for Rift Valley fever to become established to these levels and consequently the analysis is calculated to reflect the effects over a several-year period. To the losses from mortality and morbidity, as estimated on the basis of the cumulative decline in annual production, is added the capital loss associated with the herd as a reproductive and growing out or fattening unit. The impact of the spread of the disease is estimated by aggregating the losses associated with that spread across the states in which the disease has become endemic. No estimate is made of efforts to control the disease nor of the costs of this control. The numbers, therefore, represent a worst case scenario of what might happen if no control or containment measures were exercised.

The analysis suggests annual production losses associated with the disease infecting cattle equal to $56 million in California and $28 million in Florida. Capital losses would equal $76 million in California and $31 million in Florida. Together these losses would total 12% of the value of production in California and 20% of its value in Florida (model 3, Annex A).

CHAPTER 4

AFRICAN SWINE FEVER

Introduction

African swine fever is a virus that affects wild and domestic swine (Blood et al., 1983; Gillespie and Timony, 1981). Most feral swine do not show clinical signs of disease. It is however a serious threat to domesticated swine. At the present time, it is a foreign animal disease and was recently eradicated from the island countries of the Dominican Republic, Haiti, and Cuba in the Caribbean. The virus belongs to the family of viruses known as Iridoviridae, although the classification of this virus is currently under review and may be reclassified as a pox virus (Hess, 1981).

Transmission of the virus can follow several routes. First, and the one historically blamed for spread of the disease from one region of the world to another, is the feeding of raw pork products and garbage to swine (Jubb and Kennedy, 1970) Once a focus of infection is established transmission can occur by several routes. Direct contact between pigs is the most likely route but arthropod vectors, especially soft-shelled ticks, act as carriers of the disease (Blood et al., 1983).

The impact of the greenhouse effect upon the distribution and activity of tick populations could be significant enough to cause outbreaks of the disease in a variety of areas. Ornithodoros coriaceous, a tick native to the United States, has experimentally infected domestic swine (Blood et al., 1983). Haematopinus suis, the hog louse, is also a probable vector of African swine fever (Blood et al., 1983).

One can envision a scenario where African swine fever is introduced into the U.S. and arthropod vectors carry the organism into wild pig populations. Once a reservoir such as this is established, direct contact or arthropod vectors could then sporadically and repeatedly carry the disease back into domestic swine populations where it would rapidly disseminate into commercial piggeries through direct contact (Degner et al., 1983). Furthermore, once African swine fever is established in the soft tick population, it may be impossible to eradicate (Butler and Gibbs, 1984). Apparently, this situation has recently occurred in Spain where the disease has spread from Africa.

Clinical Signs, Epidemiology, and Vector Biology of the Disease

The disease is an acute generalized viremia that dramatically demonstrates damage to the vascular endothelium. As a result blood vessels break down, showing hemorrhage and edema as major clinical signs (Blood et al., 1983). Macrophages and lymphocytes are also invaded by the virus with a resulting lymphopenia (Blood et al., 1983). In chronically infected animals immune complexes may form, as evidenced by disseminated intravascular coagualopathies (Blood et al., 1983).

Signs of the disease are quite similar to hog cholera. In fact, it is difficult to distinguish the two in the field. Laboratory diagnosis in the form of virus isolation is often needed for diagnosis. In African swine fever as well as hog cholera, there are pyrexia, depression, vomiting, and diarrhea, but swine affected with hog cholera will not eat (Blood et al., 1983). In African swine fever animals continue to eat. There is no evidence that African swine fever affects man.

One important aspect of African swine fever, like many diseases that manifest extremely volatile outbreaks, is that initial epizootics show acute and peracute signs with high mortality. With the passage of time the outbreaks become less severe, mortality drops, and more diseased animals show chronic signs with a greater increase in the carrier animal state. In these cases the damage, economically and biologically, is less direct but no less debilitating.

Economic Importance of African Swine Fever

If African swine fever were to be introduced into the United States, the effects on the swine industry could be truly disastrous. Recently this disease was introduced into the island of Hispaniola. In order to eradicate the disease from the island before it was established in the soft tick population, plans were made and executed to depopulate the entire island of swine. Following this, sentinel swine were introduced for a period of time to be sure that the disease had been eradicated. Following this, the island was repopulated with swine from the United States. The level of donor assistance and loans that has been necessary to eradicate African swine fever from Haiti alone is estimated to be more than $36 million (Mulhern, 1984).

Florida has more feral swine than any other state in the Union (Degner et al., 1983). Census shows approximately 500,000 head occurring in 66 of 67 counties (Degner et al., 1983). These swine are domestic swine that have gone wild from herds imported by Spanish explorers (Degner et al., 1983). It has been projected that an annual loss of $6 million would result if the feral swine population in Florida were to be lost owing to African swine fever (Degner et al., 1983).

Control of African Swine Fever

There is no effective vaccine or treatment for African swine fever (Meyer, 1971). It has the potential for decimating swine populations where it is introduced, and once established in the tick vectors, it would be extremely difficult, if not impossible, to eradicate (Butler and Gibbs, 1984). Fortunately in Haiti and the Dominican Republic, the disease had not established itself in the Ornithodoros vectors to the extent that could prevent its eradication. Direct costs for eradication of the disease in Haiti have been documented to be more than $36 million (Mulhern, 1984).

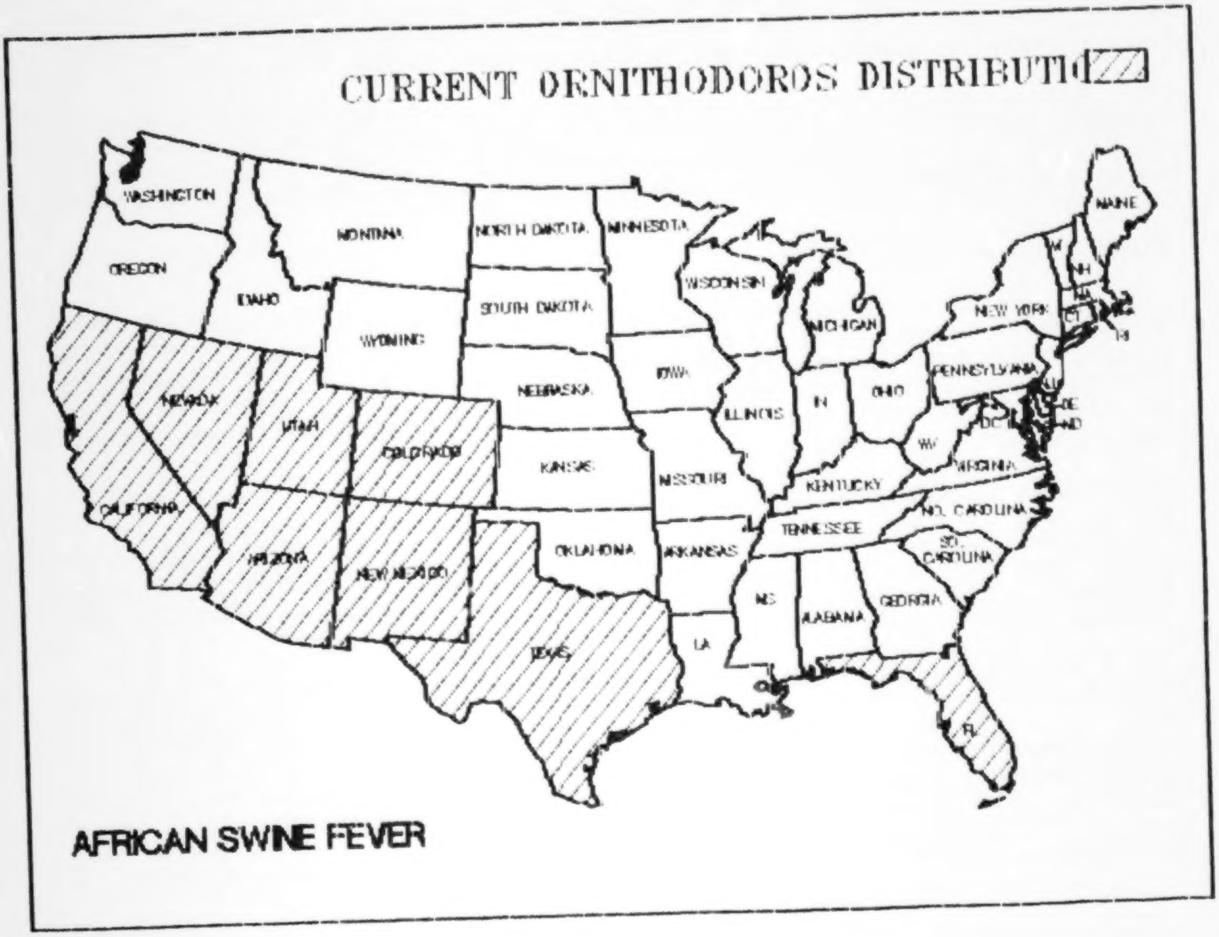
Possible Effects of Global Climate Change on African Swine Fever

Climate has the greatest effect on the vector organism. Warm-blooded vertebrate hosts moderate and maintain temperature for the virus organism. Too low a temperature induces hibernation with no transmission. Cold-blooded (poikilothermic) arthropod vectors are unable to regulate temperature and as a result climate plays an important role in the activity of vectors and the transmission of virus (Sellers, 1981).

If African swine fever is introduced into the United States and becomes established in the Ornithodoros tick reservoir, eradication of this disease may well become impossible. It has been shown that Ornithodoros ticks can live up to 11 years, and infected ticks have been able to transmit the virus to swine up to 8 years following infection (Butler and Gibbs, 1984). Furthermore, once infected, ticks can spread the virus to their offspring and through sexual contact, permitting maintenance of the disease in the tick reservoir indefinitely (Butler and Gibbs, 1984; Fraser, 1986). Because this vector is so important in the control and eradication of this disease, any expansion of its habitat proportionately increases the risk of establishment in the tick population if this disease is introduced and would be justification for increased animal disease surveillance efforts at our borders.

Changing climates, especially those projected by the GISS climate model, would be conducive to expanding habitats and populations of the tick vectors and possibly the wild or semi-wild pig populations.

The current distribution of the Onithodorus species of soft ticks that could support African swine fever can be seen in Figure 6. Environmental factors seem to be very important limiting the distribution of this tick (El Shoura, 1987; Butler and Gibbs, 1984). Experimental evidence and the present day natural distribution of these ticks show that they are able to survive hot weather quite well (El Shoura, 1987; Butler and Gibbs, 1984). Increases in temperatures enhance digestion, nutrient absorption, and egg maturation, demonstrating the important effect of temperature on the physiologic activity and reproduction of this tick (El Shoura, 1987). However, the activity of the Ornithodoros tick is affected by cool weather, as temperatures at or below 22°C significantly reduce tick activity, larval development, and reproduction (El Shoura, 1987; Cunliffe and Nuttall, 1921). Present day distribution of this tick appears to be limited to areas where temperatures are warm enough for a sufficient period of time to permit the tick to complete its rather complex life cycle.


CURRENT ORNITHODOROS DISTRIBUTI ▨
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MAINE
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GEORGIA
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AFRICAN SWINE FEVER

Figure 6. Present day distribution of African swine fever vectors: assumptions are based on present day diurnal variations of mean temperatures for the months of January and July and mean precipitation as described in the GISS and GDFL climate models, current vector distribution (Butler and Gibbs, 1984), and known vector and agent biology as presented in current literature. African swine fever does not currently occur in the United States. If introduced, through the entry of infected animals, uncooked garbage, wild swine, or other means, the shaded states are those where this disease is more likely to become established owing to present vector distribution.

The environmental changes predicted at $2xCO_2$ levels of the GISS and GFDL models would permit an expansion of the geographical distribution of this vector species of African swine fever. Generally, the distribution could be expected to expand in a northern direction, possibly extending to the northern limits of the southern states, where, if the climate model predictions are realized, the tick should be able to complete its life cycle (Figure 7). It is important to note that these projections are based on what is currently known about the biology of this vector and the predictions made by the GISS and GDFL climate models. It is possible that as yet undefined environmental or other limitations may restrict the distribution of this tick species, as further work is necessary to fully elaborate the factors limiting its distribution. The tick is likely to expand into areas where over-wintering becomes possible owing to the occurrence of milder winters in these areas. If the Onithodorus tick habitat expands northward, the implications are serious for the control and eradication of African swine fever if it is introduced into the United States.

Economic Model of the Effects of Global Climate Changes on African Swine Fever

The economic losses associated with the introduction of African swine fever into the United States, but under the assumption that various control measures are used to limit its spread, have been estimated by McCauley and Sundquist (1979). These estimates could be used to measure the increase in costs that might be incurred as a result of the projected changes in climate.

The economic consequences of African swine fever and its control in the United States were estimated under three alternative scenarios:

(1) A small outbreak of the disease is controlled and the disease is successfully eradicated through slaughter and eradication.

(2) Widespread outbreaks result in the quarantine of a larger area (e.g., a state) for a longer period of time (e.g., three years).

(3) The disease becomes endemic, and a program is mounted to reduce its incidence and eventually to eradicate it over a period of several years.

The first of these scenarios is estimated to cost about $7.3 million, of which $3 million (1977 market prices) would be used to indemnify owners of slaughtered pigs. The cost for the second scenario would be about $152 million, of which $63 million would be for indemnification. Under the third scenario, the program would cost $290 million ($211 in indemnities) over five years and $559 million ($362 in indemnities) if it had to be carried out over ten years. In addition, there would be additional losses to consumers under the third scenario equal to about $2.3 billion.

Suggested Topics For an In-depth Study on the Effects of Greenhouse-Induced Climate Changes on Pattern of Animal Health

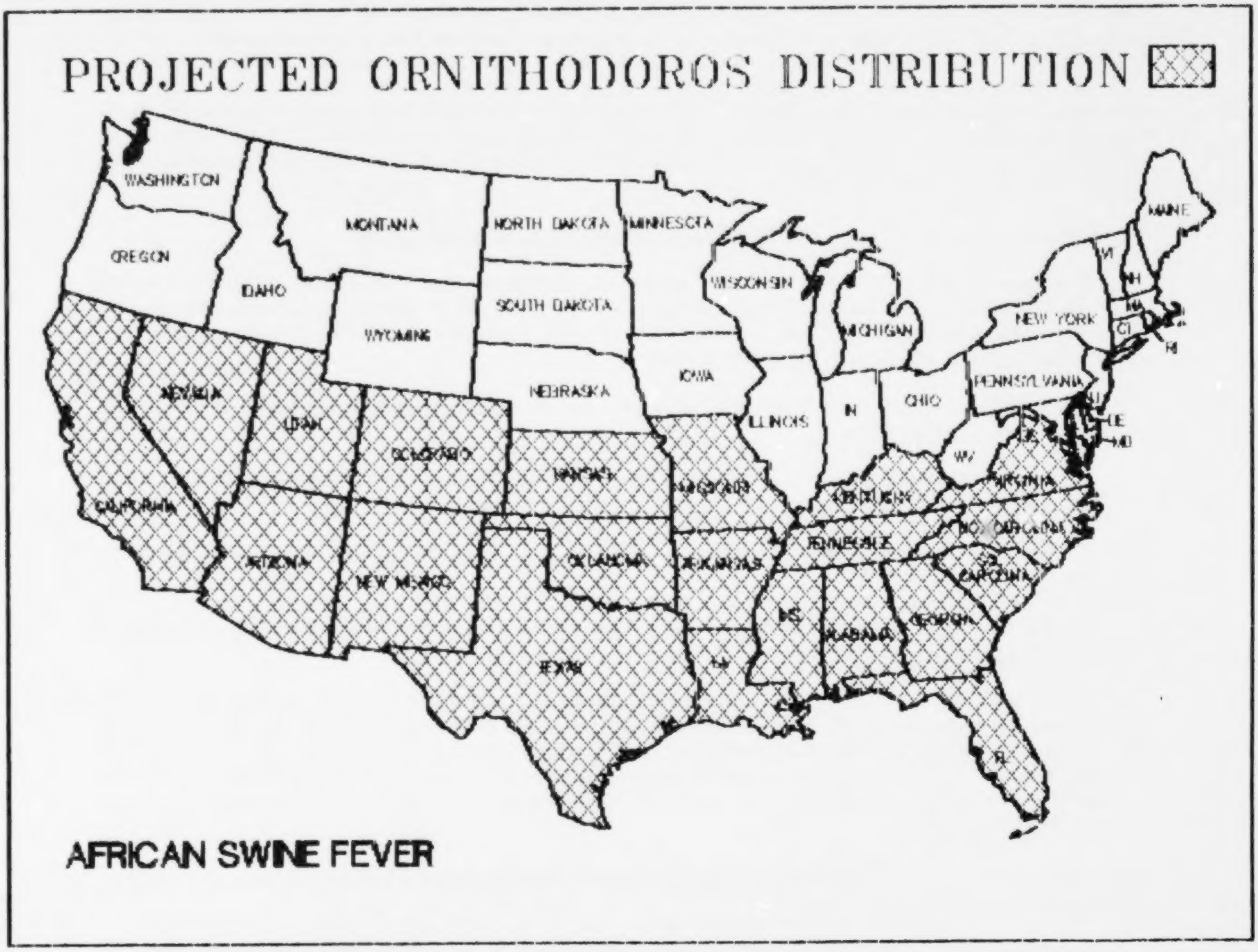
1. Consideration should be given not only to animal agriculture in the United States but also to livestock production in the world to be able to arrive at clear implications for the American livestock industry.

2. The effects of these changes on the poultry industry should be addressed in detail.

3. The effects on companion animals and animals kept for sport should be addressed.

4. Control costs should be projected for diseases examined in detail as well as the implications of the introduction, establishment, or expansion of a disease on consumers of livestock products.

5. The potential for utilizing emerging technologies such as biotechnology and genetic engineering should be examined in light of developing disease and heat stress-resistant animals.


PROJECTED ORNITHODOROS DISTRIBUTION ▨
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WYOMING
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
MINNESOTA
IOWA
WISCONSIN
MICHIGAN
ILLINOIS
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AFRICAN SWINE FEVER

Figure 7. Projected future (2xCO$_2$ levels) distribution of African swine fever vectors: projections are based on diurnal variations of mean temperatures for the months of January and July and mean precipitation predictions of GISS and GDFL climate models, current vector distribution (Butler and Gibbs, 1984), and known vector and agent biology as presented in current literature. African Swine Fever does not currently occur in the United States. If introduced through the entry of infected animals, uncooked garbage, wild swine, or other means, the shaded states are those where this disease is more likely to become established owing to the potential vector distribution.

6. Livestock management techniques should be reviewed so that recommendations may be made on reducing production losses and risks of disease introduction to farms.

7. One limitation of the analysis presented here is that it does not take into account many of the dynamic effects of the spread of disease. This would require the construction of herd projection models that would simulate the impact of changing mortality and morbidity over time. It would also involve discounting the costs associated with the disease so as to take into account the time value of money. Finally, future research should focus on the effects of disease control measures and their costs in relation to the costs associated with production losses and the decline in the capital invested in animal herds.

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ANNEX A: ECONOMIC TABLES

NOTES TO TABLES

(a) USDA, Meat Animals Production, Deposition and Income and USDA, Cattle, Sheep.

(b) Actual deaths plus mortality rates multiplied times inventory.

(c) Derived from the same sources cited in Note (a).

(d) Actual production minus average production loss due to mortality and morbidity over the course of a year.

(e) See note (a).

(f) Actual value of production from the same sources cited in Note (a). Projected value of production obtained by multiplying projected production times average price.

(g) Actual minus projected value of production.

(h) Projected minus actual deaths multiplied times average weight and price.

Model # 8: Cattle (Blue Tongue)

Key Parameters:

Region	Mortality rate cattle	Mortality rate calves	Morbidity rate cattle	Morbidity rate calves
1	7.5%	15.0%	15.0%	15.0%
2				
3				

weights: (in 100 lbs)
cattle 12.5
calves 2.25

CATTLE AND CALVES

State	Inventory Jan. 1997 (a)		Actual Deaths (a)		Projected Deaths (b)		Actual Production (c)		Projected Production (d)		Average Price per 100 pounds (e)		Total Value of Production (f)		Value of projected production loss (g)	Value of herd capital loss (h)
	Cattle	Calves	Cattle	Calves	Cattle	Calves	Cattle	Calves	Cattle	Calves	Cattle	Calves	Actual	Projected		
	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 LBS	1,000 LBS	1,000 LBS	1,000 LBS	US$	US$	1,000$	1,000$	1,000$	1,000$
Ala	1.350	490	26	34	128	108	617.151	57.619	551.193	49.624	53.30	74.40	371.810	330.706	41.104	80.261
Alas	2.753	1.70	0	1	0	1	2.590	165	2.590	165	66.20	73.00	1.835	1.835	0	0
Ariz	762	238	26	30	26	30	580.735	0	580.735	0	61.00	74.90	355.762	355.762	0	0
Ark	1.377	463	35	62	138	131	570.443	87.717	509.477	75.546	55.30	78.10	383.962	340.742	43.220	83.593
Calif	3.650	1.100	90	162	90	162	1.831.803	71,497	1.831.803	71.497	56.30	71.60	1.082.497	1.082.497	0	0
Colo	2.205	395	55	70	55	70	1.697.990	0	1.697.990	0	66.00	82.50	1.120.285	1.120.285	0	0
Conn	67	16	2	4	2	4	18.450	2.800	18.450	2.800	50.00	63.00	10.989	10.989	0	0
Del	25	6	1	1	1	1	7.414	731	7.414	731	54.20	67.80	4.514	4.514	0	0
Fla	1.725	415	35	40	35	40	125.120	299,750	125.120	299,750	47.60	79.20	296.959	296.959	0	0
GA	1,226	424	28	47	120	111	261.830	132.350	233.867	113.986	51.10	71.70	228.690	201.224	27,466	68.993
Haw	150	45	2	3	2	3	64,258	1,422	64,258	1.422	43.50	69.00	28.649	28.649	0	0
Idaho	1.235	315	18	70	18	70	708.237	43.703	708.237	43.703	59.10	77.80	452.569	452.569	0	0
Ill	1.760	510	25	50	25	50	793.199	9.191	793.199	9.191	63.00	93.00	508.263	508.263	0	0
Ind	1.080	390	26	69	26	69	354,789	63,026	354.789	63.026	55.40	68.90	239.978	239.978	0	0
Iowa	3.440	1.210	60	130	60	130	2.242.150	0	2.242.150	0	61.80	75.30	1.379,344	1.379.344	0	0
Kans	4.585	1.330	80	115	80	115	3.045.775	0	3.045.775	0	64.50	79.00	1.967.209	1.967.209	0	0
KY	1,851	599	67	93	156	123	568.776	160.664	507.988	138.372	55.20	73.90	432,695	382.666	50.029	110.729
LA	919	241	27	39	96	75	183.401	126.669	163.800	109.094	48.10	78.80	188.031	154.754	23.277	67.851
Maine	93	27	2	4	2	4	28.997	2.583	28.997	2.583	50.00	62.00	16.100	16.100	0	0
MD	264	66	5	13	5	13	83.520	22.425	83.520	22,425	54.20	67.80	60.472	60.472	0	0
Mass	69	16	2	4	2	4	13.820	1.800	13.820	1,800	50.00	63.00	8.044	8.044	0	0
Mich	1.025	300	23	70	23	70	438.281	23.849	438,281	23.849	52.50	71.90	247.245	247.245	0	0
Minn	2.473	677	50	130	50	130	1.402.278	18.417	1.402.278	18.417	58.10	78.30	829,144	829.144	0	0
Miss	1.035	338	32	45	110	96	262.879	110.941	234.784	95,461	47.70	78.70	212.625	187.120	25.505	55.262
Mo	3.310	1.290	65	130	313	324	1,053.468	246.442	940,878	212.248	61.40	75.70	833.356	738.371	95.015	223.490
Mont	2.172	228	29	55	192	99	900.969	87,591	715.366	75,696	61.10	90.70	560.320	498.175	62,145	130.623
Nebr	6.370	1.130	90	115	80	115	3,440.590	0	3.440.590	0	64.50	82.30	2.212.496	2.212.496	0	0
Nev	398	152	7	15	7	15	143.137	36.223	143.137	36.223	54.90	66.70	102.743	102.743	0	0
NH	50	12	1	2	1	2	14.040	3.300	14,040	3,300	50.00	62.00	9,066	9.066	0	0
NJ	76	16	1	2	1	2	9.060	10.315	9.060	10.315	63.20	76.20	11,776	11.776	0	0
N Mex	1.037	323	24	32	24	32	535.703	66.427	535.703	66,427	57.20	84.50	362,553	362.553	0	0
NY	1.525	329	40	87	40	87	157.091	85.169	157.091	85.169	61.40	77.50	131.026	131.026	0	0
NC	682	268	20	32	71	72	214.328	69.772	191.621	60.091	51.50	70.60	159.638	141.007	18,631	39,316
N Dak	1.543	357	18	55	18	55	652.169	96.621	652.169	96.621	64.10	81.60	496.583	496.583	0	0
Ohio	1,390	410	45	65	45	65	545,840	45,800	545.840	45.800	58.60	73.10	353.342	353.342	0	0
Okla	3.835	1.365	90	140	90	140	2,086.299	25,851	2.086.299	25.851	57.60	79.30	1,222.208	1,222.208	0	0
Oreg	1.073	327	30	50	110	93	451.595	35.720	403.420	31.626	57.80	75.00	288.987	257.212	31.775	55.531
PA	1.559	391	33	70	33	70	508,308	63.957	508.308	63.957	55.10	83.10	333.226	333.226	0	0
RI	5.7	1	0	0	0	0	1175	288	1.175	288	50.00	61.00	769	769	0	0
SC	471	149	16	22	51	44	206.273	22,677	184.228	19.530	48.30	75.10	116.887	103.845	13.042	25.156
S Dak	2.692	918	55	120	255	259	1.692.117	70.561	1,511.274	60.756	62.50	94.40	1.117.111	995.922	121.259	185.298
Tenn	1.755	645	35	90	157	187	645.010	99,745	576.075	95.014	52.20	72.60	408.384	362.453	45.931	101.629
Tex	10.500	2.900	220	280	220	280	5.367.549	77.341	5.367.549	77.341	62.10	78.70	3.394.131	3.394.131	0	0
Utah	525	165	15	42	15	42	254.903	35.622	254,903	35.622	51.80	79.40	185.814	185.814	0	0
Vt	325	150	14	87	14	57	65.787	10.383	65.787	10,383	50.00	62.00	39.331	39.331	0	0
Va	1.450	410	29	70	29	70	544.738	37,002	544,738	37.002	55.90	71.10	380.717	380.717	0	0
Wash	1.090	210	25	45	25	45	527.779	4.801	527.779	4.301	61.00	76.00	325.594	325.594	0	0
W Va	443	117	15	25	15	25	15.569	55.681	15.569	55,581	57.50	68.70	47.205	47.205	0	0
Wis	3.285	975	90	225	90	225	1.181.415	173.480	1,181,415	173,480	50.80	108.00	787.517	787.517	0	0
Wyo	1.039	261	20	35	29	76	391.767	73,243	350.076	63,080	64.30	95.30	316.511	278.906	35.605	79.146
USA	79.946	23.154	1.700	3.100	3.276	4.163	37.510.968	2,771,510	36.644.385	2.579.773	55.58	74.96	24.629.290	23.995.256	634.034	1.235.935

Model # 2: Sheep and Lambs (Blue Tongue)

Key Parameters:

Region	Mortality rate sheep	Mortality rate lambs	Morbidity rate sheep	Morbidity rate lambs	weights: in 100 lbs	
1	10.0%	25.0%	15.0%	15.0%	sheep	1.70
2					lamb	0.50
3						

SHEEP AND LAMBS

State	Inventory Jan. 1987 (a)		Actual Deaths (a)		Projected Deaths (b)		Actual Production (c)		Projected Production (d)		Average Price per 100 pounds (e)		Total Value of Production (f)		Value of projected production loss (g)	Value of herd capital loss (h)
	Sheep	Lambs	Sheep	Lambs	Sheep	Lambs	Sheep	Lambs	Sheep	Lambs	Sheep	Lambs	Actual	Projected		
	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 LBS	1,000 LBS	1,000 LBS	1,000 LBS	US$	US$	1,000$	1,000$	1,000$	1,000$
Alas	2	0	0	0	0	0	16	16	16	16	30.00	75.00	17	17	0	0
Ariz	157	126	9	11	9	11	6,275	6,265	6,275	6,265	21.40	74.80	6,029	6,029	0	0
Calif	716	264	57	60	57	60	4,629	90,825	4,629	90,825	25.10	74.90	69,190	69,170	0	0
Colo	319	371	20	40	20	40	8,069	37,720	8,069	37,720	32.00	74.60	30,721	30,721	0	0
Conn	6	2	0	1	0	1	230	494	230	494	39.00	93.00	569	569	0	0
Idaho	258	63	17	20	17	20	3,860	26,700	3,860	26,700	24.00	74.10	20,711	20,711	0	0
Ill	85	34	6	14	6	16	674	7,186	674	7,186	23.70	75.50	5,585	5,585	0	0
Ind	67	24	4	8	4	9	1,731	5,054	1,731	5,054	27.50	70.40	6,036	6,036	(0)	0
Iowa	268	107	19	49	19	49	4,465	28,986	4,465	28,986	29.40	74.80	23,003	23,003	0	0
Kans	156	82	6	12	6	12	1,270	16,667	1,270	16,667	30.40	74.50	12,803	12,803	0	0
KY	26	6	3	5	5	5	760	1,907	637	1,597	23.00	75.00	1,605	1,344	261	124
LA	13	3	1	2	5	3	149	542	124	454	33.00	80.00	483	405	78	85
Maine	14	4	0	1	0	1	393	862	393	862	39.00	87.00	903	903	0	0
MD	19	6	1	2	1	2	1,082	900	1,082	900	25.30	75.90	957	957	0	0
Mass	10	4	1	1	1	1	408	543	408	543	39.00	95.00	675	675	0	0
Mich	72	36	4	12	4	12	1,345	7,411	1,345	7,411	25.00	75.00	5,894	5,894	0	0
Minn	138	99	10	21	10	21	2,428	15,592	2,428	15,592	24.60	75.60	12,385	12,385	0	0
Mo	86	26	7	16	15	19	1,678	6,507	1,238	5,449	37.00	76.00	5,492	4,600	892	628
Mont	386	139	45	45	83	59	10,880	26,482	9,112	20,503	27.40	80.50	22,689	19,002	3,687	2,348
Nebr	101	72	10	19	10	19	2,420	10,513	2,420	10,513	29.40	77.70	8,880	8,880	0	0
Nev	71	15	7	20	7	20	1,295	5,181	1,295	5,181	25.70	71.30	4,027	4,027	0	0
NH	9	3	0	1	0	1	294	551	294	551	39.00	91.00	616	616	0	0
NJ	9	5	1	2	1	2	608	638	608	638	42.40	58.80	633	633	0	0
N Mex	363	117	33	40	33	40	5,769	13,550	5,769	13,550	35.90	83.30	13,263	13,243	0	0
NY	62	22	6	6	6	6	1,820	1,844	1,820	1,844	30.10	76.50	1,960	1,960	0	0
NC	10	3	1	2	2	2	186	529	156	443	28.00	69.00	417	369	48	38
N Dak	125	60	10	15	10	15	3,875	9,871	3,875	9,871	24.80	78.20	9,680	9,680	0	0
Ohio	210	93	12	22	12	22	2,480	14,580	2,480	14,580	33.30	77.10	12,067	12,067	0	0
Okla	66	41	6	8	6	8	1,676	4,378	1,676	4,378	22.50	76.10	3,709	3,709	0	0
Oreg	269	144	20	31	67	46	7,605	29,160	6,370	24,421	25.30	75.80	23,875	19,995	3,880	1,619
PA	79	25	6	10	9	10	2,342	4,142	2,342	4,142	26.40	79.50	3,911	3,911	0	0
S Dak	449	156	30	60	75	76	10,721	43,736	8,979	36,627	34.90	84.50	40,697	34,084	6,613	3,322
Tenn	9	4	1	1	2	1	271	356	244	298	28.50	81.83	374	313	61	60
Tex	1385	344	80	62	80	62	36,994	78,881	36,994	78,881	33.00	84.80	79,099	79,099	0	0
Utah	387	77	24	41	24	41	4,599	31,574	4,599	31,574	21.40	71.60	23,591	23,591	0	0
Vt	12	4	1	2	1	2	393	680	393	680	39.00	87.00	765	765	0	0
Va	105	63	7	11	7	11	2,986	6,705	2,886	6,905	22.00	77.00	5,952	5,952	0	0
Wash	66	13	4	6	4	6	2,130	4,337	2,130	4,337	24.00	74.40	3,738	3,738	0	0
W Va	71	19	5	12	6	12	1,541	4,144	1,541	4,144	25.70	74.10	3,436	3,436	0	0
Wis	57	26	5	8	5	5	1,922	5,717	1,922	5,717	24.50	74.10	6,707	6,707	0	0
Wyo	555	220	25	34	80	56	17,708	32,185	14,830	26,955	27.50	80.70	30,843	25,831	5,012	3,482
USA	7212	3122	505	731	684	801	159,698	552,109	151,609	559,457	29	78	498,925	478,373	20,552	11,727

Model # 3: Cattle (Rift Valley Fever)

Key Parameters:

Region	Mortality rate		Morbidity rate		weights: in 100 lbs)	
	cattle	calves	cattle	calves		
1	2.0%	14.0%	5.0%	5.0%	cattle	12.5
2					calves	2.25
3						

CATTLE AND CALVES

State	Inventory Jan. 1937 (a)		Actual Deaths (a)		Projected Deaths (b)		Actual Production (c)		Projected Production (d)		Average Price per 100 pounds (e)		Total Value of Production (f)		Value of projected production loss (g)	Value of herd capital loss (h)
	Cattle	Calves	Cattle	Calves	Cattle	Calves	Cattle	Calves	Cattle	Calves	Cattle	Calves	Actual	Projected		
	1,000 HD	1.000 HD	1,000 HD	1,000 HD	1,000 HD	1,000 HD	1.000 LBS	1,000 LBS	1,000 LBS	1,000 LBS	US$	US$	1.000$	1.000$	1,000$	1.000$
Calif	3.650	1.100	90	162	163	316	1.831.803	71.497	1,741,678	64.033	56.30	71.60	1.092.497	1.026.412	56,085	76.183
Fla	1.725	415	35	40	70	93	125.120	299.750	118,964	268.456	47.60	79.20	296.959	269,244	27,715	30.881

EFFECT OF CLIMATIC WARMING ON POPULATIONS OF THE HORN FLY, WITH ASSOCIATED IMPACT ON WEIGHT GAIN AND MILK PRODUCTION IN CATTLE

by

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FINDINGS[1]

Climatic warming predicted under a doubling of atmospheric carbon dioxide (GFDL, $2xCO_2$) will have a pronounced effect on populations of the horn fly, a widespread pest of pastured cattle. Throughout most of the United States, annual adult horn fly activity will commence 4 to 6 weeks earlier in the spring, average 100 to 400 flies per head higher through the summer, and strongly persist 4 to 6 weeks longer in the fall. This condition will (1) cause substantial reductions in the seasonal average weight gain of growing beef cattle (range 2 to 12 kg/head), and (2) represent a potentially important new stress on dairy cattle in northern dairy regions. In contrast, horn fly populations from Mississippi west to Texas and southern California will be suppressed by maximum summer temperatures; this will result in weight-gain losses in beef cattle that are less than those currently experienced, especially in Texas.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Contract No. W12932972-01-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER I

INTRODUCTION

DESCRIPTION OF THE ECOLOGICAL SYSTEM

This assessment of the impact of $2xCO_2$-induced climatic warming on animal health focuses on the relationship between climate, an ectoparasite (the horn fly), and growth and milk production in domestic cattle.

Horn Flies, Cattle, and Economic Losses

The horn fly, Haematobia irritans L., is a ubiquitous pest of pastured cattle throughout the United States, commonly attaining levels of 300 to 500 flies per head on untreated stock. Adult horn flies live on cattle and derive nutrition by blood feeding from their host ca. 20-30 times per day (Harris et al., 1974). This activity causes annoyance and irritation that is reflected behaviorally as head throwing, skin rippling, and tail switching (Harvey and Launchbaugh, 1982). Economic loss attributable to the horn fly is expressed as a reduction in weight gain and milk production, as well as less efficent feed conversion (Steelman, 1974). Estimates of horn fly-induced reductions in average daily weight gain (ADG) in beef cattle range from negligible to 0.2 kg per head per day (Drummond, 1987). Losses in milk production due to horn flies have been estimated at 80 million dollars annually (Anonymous, 1976), or one percent of total milk production (Drummond et al., 1981). Recently, the collective loss in beef and dairy cattle production due to horn flies was estimated at 730.3 million dollars annually, irrespective of control costs (Drummond, 1987).

Horn Flies and Temperature

Like many insects, the phenology and density of horn fly populations are regulated largely by temperature (Bruce, 1964). Annual adult horn fly activity commences with warming ambient temperature in spring (March-May), and thereafter successive overlapping generations are produced until decreasing temperature and daylength in the fall trigger an overwintering diapause. In general, the climatic conditions projected for a doubling of carbon dioxide in the atmosphere can be anticipated to (1) extend the seasonal duration of horn fly activity during both spring and fall months, and (2) accelerate horn fly population growth/activity, with the result that greater numbers of flies will occur on cattle during favorable periods; also, extreme summer temperatures may be lethal.

Climate and Insect Population Models

The use of deterministic, climate-driven models to predict the seasonal abundance of insect populations is an accepted procedure widely used to estimate population growth in insects (Haynes and Tummala, 1976). Such models are typically based on life-stage-specific, temperature-dependent growth rates, and can be run with real or substituted temperature values. This report describes the application of a deterministic population model (Miller, 1986) to estimate the effect of $2xCO_2$-induced climatic warming on populations of the horn fly; the results are used to estimate reductions in weight gain for beef cattle and milk production in dairy cattle.

CHAPTER 2

METHODOLOGY

THE EFFECTS MODEL

Description of the Model

The abundance of horn flies under $2XCO_2$-induced climatic warming (GFDL output) was predicted on a monthly basis using the horn fly population model of Miller (1986). The model is based on life-stage-specific growth and survival characteristics of the horn fly, as determined by temperature and rainfall. Monthly horn fly population levels were estimated on the basis of climatic conditions predicted for nine states: California, Idaho, Texas, Nebraska, Minnesota, Mississippi, Kentucky, Florida, and Maryland.

Limitations Resulting from the Model

Horn fly population levels predicted for average temperatures >40°C (104°F) cannot be compared with current horn fly densities, since these temperatures now occur only in Southwestern deserts where cattle are confined in feedlots during the summer months and therefore are not exposed to horn flies. Model predictions of horn fly phenology/density are based on 30-year climatic averages, whereas the current horn fly data are based on fly counts taken at various times of the season under variable weather and animal management conditions and by various individuals. Nevertheless, existing horn fly densities generally correlate closely with those predicted by the model with concurrent ambient temperature and rainfall (Miller, 1986). Though not a limitation of the model, it should be noted that our interpretation of economic loss associated with predicted horn fly levels is based on existing cattle management practices, breeds, and distribution; possible changes in these factors and their impact on cattle production are beyond the scope of this study. We know of no reason to suspect that a doubling in atmospheric carbon dioxide alone will account for the changes in horn fly population density or phenology predicted by $2xCO_2$-induced climatic warming.

THE SCENARIOS

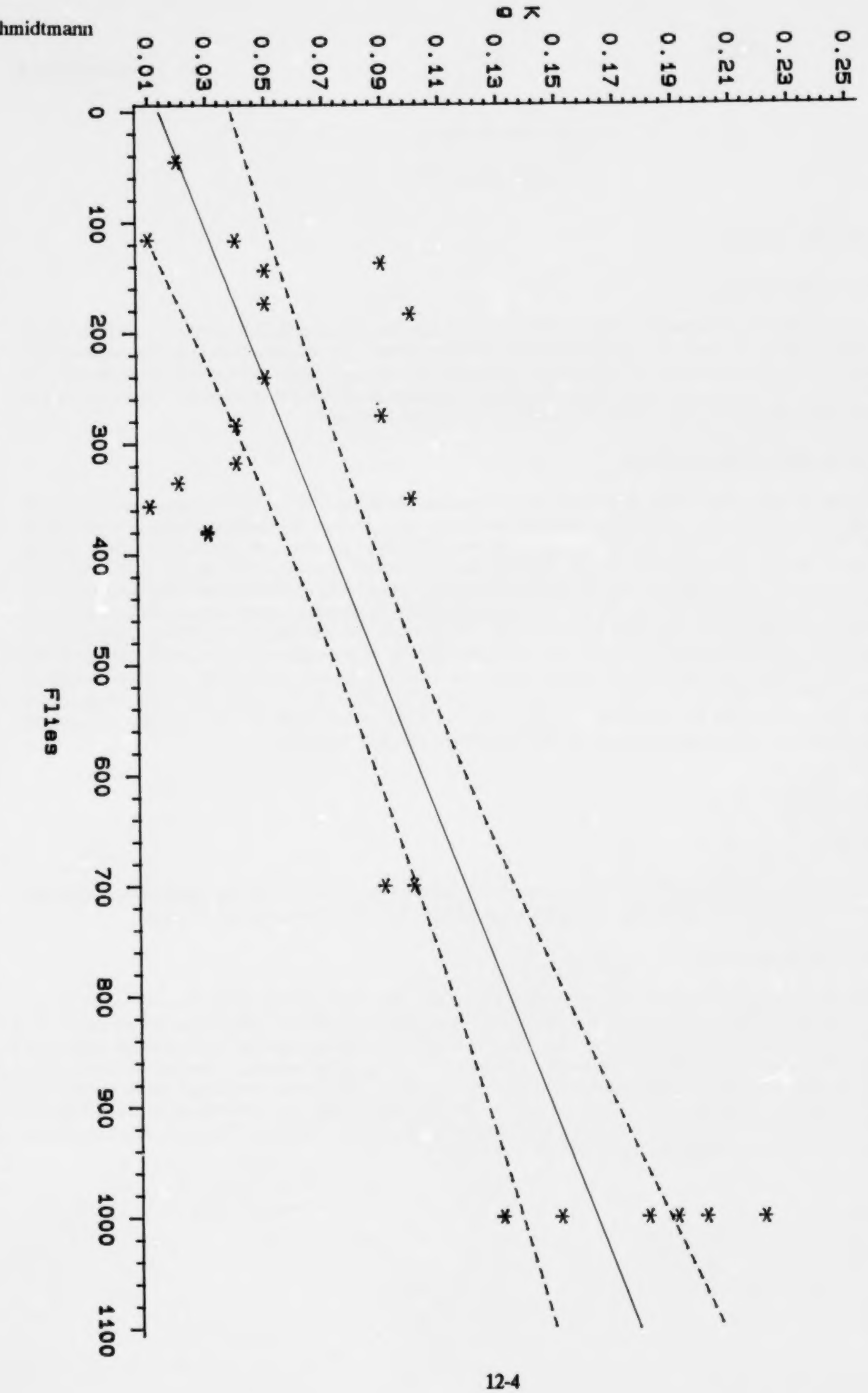
Scenario Used

The climatic scenario used to estimate horn fly abundance was the GFDL-$2xCO_2$, using values projected for temperature in degrees Celsius and precipitation as percent departure from current averages.

Estimation of Economic Loss

The effect of projected horn fly population levels on weight gain in beef cattle was estimated by the following procedure. First, the relationship between horn fly population levels and rate of gain in beef cattle was examined by computing various regressions for horn fly level (independent variable) and average daily gain (ADG) for growing beef cattle (calves and feeder/stocker cattle) (dependent variable). Twenty-five data points representing available economic loss values (see review by Drummond, 1987) were used; three outlier values that did not represent the majority of data were not used. The best estimate for the relationship between horn fly population level and reduction in ADG was the linear regression $Y = 0.14 + 0.0002X$ (Figure 1). The correlation coefficient, $r2 = 0.71$, is statistically significant ($p = <0.05$).

Figure 1. Relationship between numbers of horn flies and reduction in average daily gain (ADG) in kg.



Linear regression with 95% confidence limits on mean predicted values.

The effect of projected horn fly levels on weight gain was estimated by using model-predicted horn fly levels in the horn fly - ADG regression. Reductions in ADG corresponding to monthly horn fly levels that equaled or exceeded 100 flies/head were calculated for each state. These values were then multiplied by 30 to give the monthly reduction in weight gain attributable to horn flies. Monthly weight gain reductions were linked with the growth of calves and feeder/stocker cattle (steers and heifers) by summing monthly reductions across the periods that calves and feeder/stocker cattle are exposed to horn flies in respective states. We assumed a 7-month horn fly-exposure period (from birth to weaning) for calves, based on spring calving in northern and central states, fall calving in California, and "year around" calving in Florida and Texas. For feeder/stocker cattle, a 4-month (late spring into summer) period was assumed for exposure to horn flies.

Weight gain values calculated under climatic warming were then compared with reductions in weight gain based on current horn fly levels. This value was then multiplied by the numbers of beef calves and stocker/feeder animals by state (Anonymous, 1986). The numbers of stocker/feeder cattle used in calculations represent the numbers of steers (= stockers) plus 75 percent of heifer calves (= feeders from the calf crop of the preceding year); the balance of heifers remain with herds as replacement cows. The resulting weight gain values, either increases or decreases relative to current horn fly-induced losses, represent the change in weight gain that will be experienced by calves and feeder/stocker cattle due to horn flies under climatic warming.

CHAPTER 3

RESULTS

HORN FLY PREDICTIONS: CHANGES, CAUSES, AND EFFECTS

Horn Fly Density and Seasonal Activity

When compared with existing population levels (Figure 2), the numbers of horn flies that will occur under climatic warming differ dramatically; both increases and decreases will occur. Conditions favoring increases in horn fly levels will occur in all areas of the U.S. except the southern states from Mississippi west to central California; in this area, horn fly populations will be suppressed during the summer months. As illustrated by projected monthly population levels (Figure 2), adult horn fly activity throughout most of the United States will increase rapidly during the spring months under climatic warming (see Florida, Idaho, Maryland, Minnesota, and Nebraska), and summer population levels will be higher than current horn fly levels. Also, high-level horn fly activity will persist during the fall months, with populations that exceed 500 flies per head experienced throughout central and northern areas of the United States; current horn fly levels average ca. 100 to 300 flies per head in these areas during this period. Thus, climatic warming will (1) expand the length of time that cattle are exposed to economically important levels of horn flies, and (2) increase the density (number of flies per animal) of many populations, especially during spring and fall months.

Cause of Changes in Horn Fly Populations

The results indicate that ambient temperature is the primary factor underlying projected changes in horn fly population levels. The marked increase in duration and intensity of horn fly activity projected for Northwest and Midwest regions, where increases in temperature will occur but precipitation will remain stable or decrease slightly, support this interpretation. Also, ambient temperature exceeding 34°C for two hours (= 44°C in cattle dung pats) is lethal to immature horn flies (Palmer and Bay, 1984); as the model predicts, a summer depression of horn fly density will be pronounced, particularly in southern states.

Effect on Weight Gain in Beef Cattle

The exposure of beef cattle to greater numbers of horn flies for longer periods will increase reductions in weight gain; the weight of cattle will be reduced by from ca. 2 to 12 kg/head across most of the U.S. (Table 1). The greatest weight reduction per animal will occur in the mid-Atlantic region, but the Northwest, Southeast, and the Midwest regions will also experience considerable losses. In Nebraska, for example, projected increases of 225-250 horn flies/head will result in greater weight reductions of 10.2 and 5.1 kg/head for calves and feeder/stocker cattle, respectively. For the 17,728,000 calves and 1,851,000 feeder/stocker animals in the state, total reductions in weight will total 27,168,100 kg greater than currently experienced.

Summer Suppression of Horn Flies

During the summer months, horn fly populations from Mississippi across to southern California will be suppressed under climatic warming (Figure 2). Predicted spring and fall climatic conditions will be favorable for horn flies, but summer temperatures will limit horn fly larval (maggot) survival in cattle dung pats and populations will decline. The net effect will be fewer horn flies over fewer days, hence less impact on cattle. The summer suppression of horn fly activity will be strongly expressed in Texas, and horn fly-induced reductions in weight gain will be 10.5 and 9.6 kg/head less than currently experienced by calves and feeder/stocker cattle, respectively.

Horn Flies and Dairy Cattle

The levels of horn flies projected for the upper Midwest, Northeast, and mid-Atlantic regions, which exceed current levels by several hundred flies/head from May through October, will be associated largely with dairy cattle. Economic losses in milk production due to increased horn fly activity under climatic warming cannot be reliably predicted with available data. However, it is reasonable to assume that losses in response to increased horn fly-induced annoyance and irritation will exceed either the estimated 80 million dollars in reduced milk production, or the 1 percent loss in milk production that are estimated to occur with existing levels of horn fly activity.

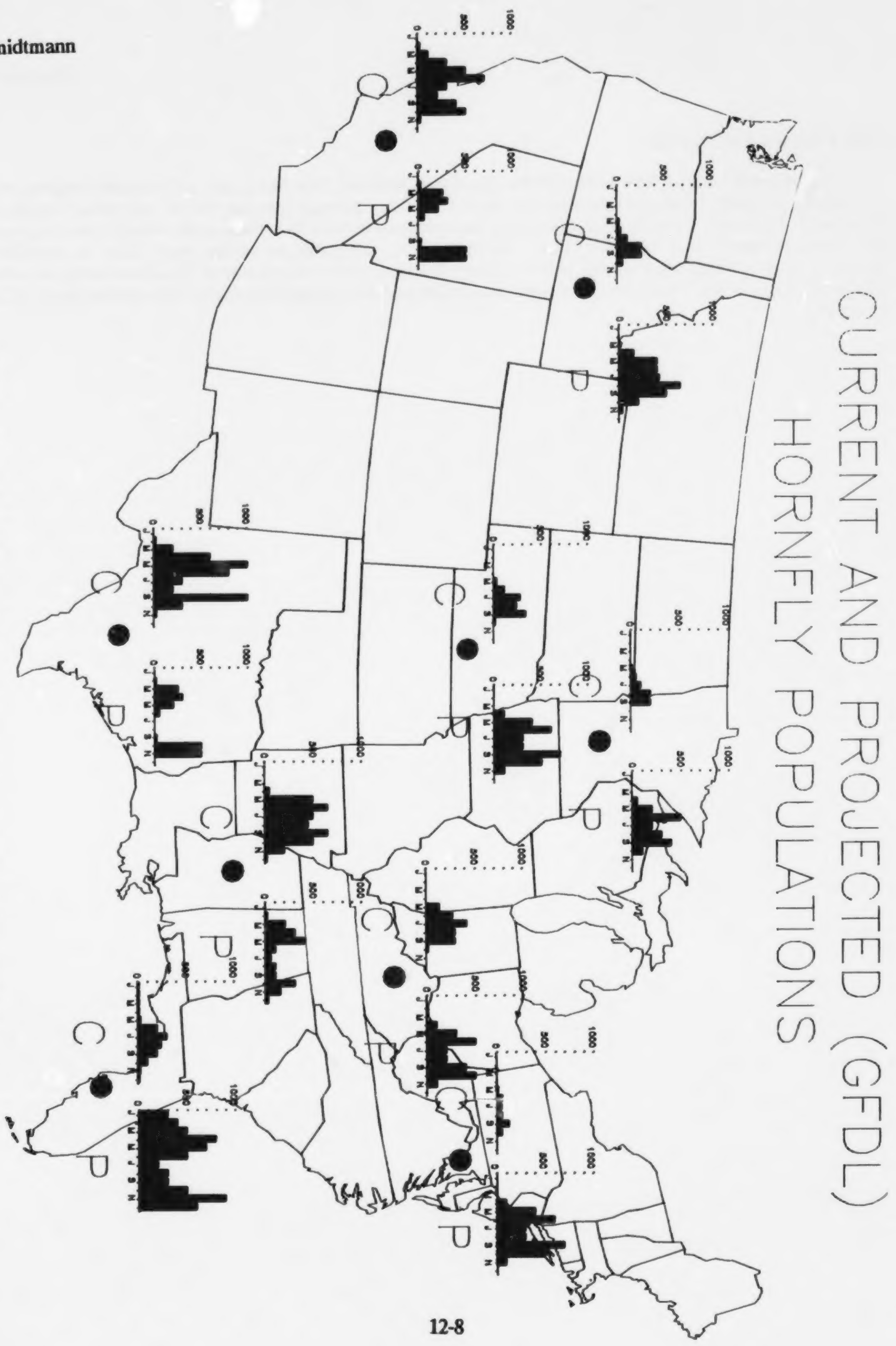

CURRENT AND PROJECTED (GFDL)
HORNFLY POPULATIONS
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Figure 2. Current hornfly populations and projected hornfly populations (GFDL).

Table 1. Summary of current and projected horn fly densities and associated changes in weight gain for beef cattle.

State	Average number of horn flies per month per head			Average reduction in weight gain per head (kg)			No. cattle (x1000)[1]		Change in weight gain (kg)	
	Current	Projected	Difference	Current	Projected	Difference[2]	Calves	Feeders/Stockers	x1000	Total
California										
calves	139	182	+ 43	5.4	7.1	+ 1.7	950		+ 1650	- 7,085,300
feeders/stockers[3]	400	200	-200	9.0	4.5	- 6.3		1381	- 8700	
Florida										
calves	105	530	+425	6.3	18.9	+12.6	1135		+14301	+15,899,400
feeders/stockers	105	530	+425	3.6	10.8	+ 7.2		222	+ 1598	
Idaho										
calves	104	393	+289	3.9	15.9	+12.0	526		+ 6312	+10,066,800
feeders/stockers	100	475	+375	2.4	10.8	+ 8.4		447	+ 3758	
Kentucky										
calves	200	243	+ 43	8.5	10.2	+ 1.7	976		+ 1659	+ 2,478,400
feeders/stockers	200	275	+ 75	4.9	6.6	+ 1.7		482	+ 819	
Maryland										
calves	48	414	+366	0.9	16.2	+15.3	71		+ 1086	+ 1,554,000
feeders/stockers	46	400		0	9.0	+ 9.0		52	+ 468	
Minnesota										
calves	82	243	+161	3.3	10.2	+ 6.9	396		+ 2732	+ 6,672,800
feeders/stockers	138	350	+212	3.3	8.1	+ 4.8		821	+ 3941	
Mississippi										
calves	304	164	-140	11.4	7.2	- 4.2	686		- 2881	- 2,860,300
feeders/stockers	294	250	- 44	6.2	6.3	+ 0.1		207	+ 21	
Nebraska										
calves	154	412	+258	6.3	16.5	+10.2	1738		+17728	+27,168,100
feeders/stockers	175	400	+225	4.2	9.3	+ 5.1		1851	+ 9440	
Texas										
calves	445	135	-310	17.5	7.0	-10.5	5178		-54329	-88,389,900
feeders/stockers	675	138	-537	14.1	4.5	- 9.6		5548	-34060	

---

[1] + values represent weight gain losses greater than currently experienced; - values represent losses less than currently experienced.

[2] Data taken from Agricultural Statistics, 1986.

[3] Values represent 75% of heifer calves (= feeders) plus steers (= stockers).

CHAPTER 4

IMPLICATIONS OF RESULTS

ECONOMIC IMPLICATIONS

The economic implications of projected increases and decreases in horn fly populations are several-fold. Most notably, the exposure of beef and dairy cattle across most of the United States to both longer periods and higher levels of horn fly activity will (1) clearly result in increased reductions in weight gain for beef cattle, and (2) probably suppress milk production and certainly increase control costs for dairy cattle.

Beef Cattle

Assuming an average market sale price of $55/100 lbs. (Anonymous, 1986), losses due to increased horn fly activity (based on the nine states investigated) will range from approximately 2 to 30 million dollars per state in reduced beef sales annually. Only states from Mississippi west to southern California will be spared reductions in beef production.

The ca. eight million plus head of beef cattle (calves and feeder/stocker cattle) affected by horn flies in Texas represent ca. 15 percent of cattle in these age classes in the United States. Under climatic warming, Texas cattle will sustain economic losses greater than those currently experienced during spring and fall months, but this condition will have little effect on the strong overall economic benefit that will accrue from a summer suppression of horn fly activity. As compared with current horn fly-induced reductions in weight gain, losses under climatic warming will be as much as 10.5 and 9.6 kg/head less in calves and feeder/stocker cattle, respectively. This will amount to increased beef production of ca. 86 million kg. annually; on a monetary basis, this represents ca. 104 million dollars in beef sales.

Dairy Cattle

The economic impact of increased horn fly activity in the Great Lakes and Northeast dairy regions is less readily interpreted. Few data are available concerning the effect of horn flies on milk production, and those that have been conducted are confounded by the presence of other fly species, e.g., stable flies (Morgan and Bailie, 1980) and face flies (Burton et al., 1984). It is, however, reasonable to infer that higher levels and longer periods of horn fly activity will be expressed as losses that exceed either the 1 percent reduction in milk sales or the 80 million dollars in reduced production that are estimated for current horn fly populations (Drummond et al., 1984; Anonymous, 1976). However, the trend toward confinement housing of cattle in free-stall barns in the Northeast, which precludes horn fly attack, may offset any effect of increased horn fly activity. The decreased horn fly levels projected for the Southwest will have little impact on dairy cattle, as horn flies are uncommon in the drylot-type holding areas of the large dairy operations common to this region.

SOCIOECONOMIC IMPLICATIONS

It is reasonable to assume that higher levels and longer periods of horn fly activity, along with increased economic losses, will intensify the need for methods to suppress horn fly populations. Current horn fly control strategies are limited to the application of insecticides, either directly to cattle (primarily as insecticide-impregnated ear tags), or as feed additives fed to animals that render the manure toxic to immature stages. A dependency upon chemical control has in recent years resulted in a rapid selection for genetic resistance (Schmidt et al., 1987). Since horn flies in many states are now resistant to chemicals registered for their control, alternative horn fly control methods, including practices safe for lactating cows, will be necessary under climatic warming to offset increased losses in animal production.

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AGRICULTURAL POLICIES FOR CLIMATE CHANGES INDUCED BY GREENHOUSE GASES

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FINDINGS[1]

Climate changes caused by ever-increasing quantities of greenhouse gases released by human activities are expected to have a significant effect on U.S. agriculture and rural America. Among other things, these effects are expected to include: (1) significant shifts in the location of agricultural production within the United States; (2) major changes in land and water use; (3) significant geographic shifts in population and rural industries; (4) important environmental effects from changes in fertilizer and pesticide runoff; (5) impacts on biodiversity and availability of germ plasm; (6) significant shifts in international comparative advantage; and (7) increased risk and uncertainty for agriculture.

This paper addresses the policy issues associated with these prospective effects. There are at least two dimensions to this problem. First, agriculture itself is an important source of greenhouse emissions. This raises the issue of what policies or policy changes are appropriate and necessary to reduce these emissions. Second, climate changes will have significant changes on the configuration of U.S. agriculture and rural America. This raises the issue of what policies are needed to facilitate the inevitable adjustments, and what policies are needed to assure that the agricultural and rural sectors contribute in an efficient and equitable way to the further development of the U.S. economy.

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CHAPTER 1

IMPORTANCE AND COMPLEXITY OF THE PROBLEM

A number of factors contribute to the importance and complexity of these problems. First, much of North America's agricultural production takes place under dryland conditions using annual crop species under technologically advanced cropping systems that are primarily monocultural in nature. The robustness associated with general, multiple-enterprise farms has, long since passed from the scene on any economically significant scale. Thus we are left with an agricultural system constituted mostly of specialized farms producing commodities in geographically specialized patterns. This system is vulnerable to changes in climate, and adjustment costs can be quite high.

Second, U.S. agriculture is an integral part of a global, international agricultural sector. Consequently, agricultural policies cannot be devised for U.S. agriculture in isolation from the rest of the world. The optimal configuration of agriculture will thus depend very much on how changes in climate affect global agriculture. In addition, it will depend very much on the policy responses of other countries to the changes in climate.

Third, the knowledge base on which sound agricultural and economic policies can be conceived and articulated is extremely weak. The precise effects of climate changes on technical agriculture are unknown even in the United States, to say nothing of the rest of the world, and especially in developing countries. In the same way, we know little in a systematic or parametric way about the response of farmers and people in the rural sector to the changes in climate.[2]

Because of these problems, the best that one can do is focus on general principles that provide guidelines for the development of policy. In that regard, the basic principles that have guided our own policy prescriptions are to let markets be the basis for facilitating the multifarious adjustments needed, and to use government interventions only when there are clear cases of externalities in which private costs and benefits are significantly different from public costs and benefits, respectively.

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[2] We do know, however, that after the adverse weather of the mid-1930's and mid-1950's, there were substantial changes in cultural practices in the Great Plains to reduce erosion and to conserve or more effectively use moisture. These changes included, for example, the replacement of the moldboard plow and an increase in the use of summer fallowing.

CHAPTER 2

REDUCING AGRICULTURAL SOURCES OF GREENHOUSE EMISSIONS

There are three sources of greenhouse emissions from agriculture: (1) the use of nitrogen fertilizers; (2) the cultivation of rice; and (3) enteric fermentation in domestic animals, with cattle being the major culprit. Policy measures should be directed to reducing these emissions so that agriculture's contribution to the greenhouse effect is reduced to a minimum.

Nitrogen Fertilizers

It happens that current agricultural policies[3] contribute to augmenting greenhouse emissions in each of the above cases. For example, target prices and loan levels set above what would otherwise be market-clearing levels increase the demand for fertilizer. Land set-asides to bring production into balance attenuate somewhat the effect of higher commodity prices on the demand for fertilizer. However, land set-asides also cause farmers to search for land substitutes, and fertilizers are an excellent land substitute. Eliminating these commodity programs and shifting to a more market-oriented policy would reduce the demand for fertilizer and in turn the supply of emissions to the atmosphere.

Rice Cultivation

Rice is not one of the major crops in the United States, although regionally it is relatively important in places such as Arkansas, California and Louisiana. Moreover, this nation produces more rice than it should according to efficiency criteria by virtue of commodity programs that set the price of rice above what it would be in the absence of such programs. Similar to the case of fertilizer, commodity programs that were more market oriented, with income transfers to farmers decoupled from the price of the commodity, would lead to a decline in the production of rice and thus to a reduction in greenhouse emissions.

Globally, the expectation is that the consumption of rice will decline in relative terms as economic development proceeds, and perhaps eventually in absolute terms. The income elasticity of demand for rice is relatively low so as per capita incomes rise worldwide, and especially in South and Southeast Asia, consumers will increase their consumption of fruits, vegetables, and livestock products. Equally as important, consumption of rice is time-intensive in the household since, compared to wheat bread, for example, it takes more time to prepare. Bread is "manufactured" in bakeries and becomes a convenience food in the household, while rice has to be cooked, with all that that entails.

As national economies expand and develop and the opportunity costs of time to the household rise, there will be added incentive to shift away from the consumption of rice to the consumption of other cereals. Opportunity costs of time in the household rise as wage rates rise and as women participate increasingly in the nation's work force.

Globally, this shift in consumption patterns away from rice suggests the importance of diversification policies to help shift resources out of the production of rice. Given the importance of irrigated rice in Asia and the lack of mobility of resources in the production of irrigated rice, adjustment of resources out of this activity can be expected to be relatively slow. A full panoply of policies, ranging from expanded and diversified agricultural research efforts, changes in irrigation infrastructure, changes in marketing infrastructure, and proper price incentives, will be needed to facilitate and accelerate the rate at which resources are adjusted out of the sector.

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[3] For an overview of these policies, see B. Gardner's, The Governing of Agriculture, Lawrence, Kansas: Regent's Press, 1981.

Economic policies in some Asian countries also encourage the excess production of rice. Japan is a classic case in which price policies encourage the production of more rice than the domestic economy can effectively absorb, and consumption policies keep the price of wheat and other commodities high relative to the price of rice, thereby causing the consumption of rice to be higher than it otherwise would be. These policies should be the subject of international negotiations designed to change the policies to reflect comparative advantage principles.

Ruminant Animals

U.S. commodity programs also encourage a cattle herd in this country that is much larger than it otherwise would be. Dairy policies in particular have for over a decade contributed to the excess production of milk by a number of means. First, the price of milk has been set above market-clearing levels, thus encouraging the production of excess supplies.[4] The cattle herd would be significantly lower if it weren't for these policies, even granting that a decline in production per cow would attenuate this reduction somewhat.

The marketing orders[5] which are an integral part of dairy policy discourage the adoption of available technology in the processing sector. This also causes the production capacity in the sector to be larger than it would otherwise be.

Notable in this regard is the failure to take full advantage of technology which makes it possible to reconstitute milk components in such a way that the reconstituted product cannot be distinguished from fresh milk either by consumer taste panels or by laboratory tests.[6] This technology makes it possible to extract the water from milk and convert it into powdered form. The powder can then be transported long distances at lower cost, thus making it possible to produce the milk in low-cost regions. In addition, the powdered product can be transported through time by storing. In this way, full advantage can be taken of the flush season of production and the product carried into the slack production time of the year. Present policies, which encourage herd sizes to meet needs in the slack season when costs of production are highest, could thus be abandoned and a smaller cow herd would be needed.

Whether the milk is transported geographically or through time, reconstituting it is fairly simple. The need is to add water, and a modest proportion of fresh milk to provide taste.[7]

Milk marketing regulations embedded in marketing orders reduce the incentive to use this technology. They do this by requiring that the reconstituted milk be priced at the same price as the higher cost fresh milk. There is thus no incentive to invest in the equipment and operating costs needed to use the technology. Elimination of this regulation would reduce the size of the dairy herd, while at the same time using resources more efficiently and making the final product available to consumers at a lower cost.

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[4] Over the last decade, these excess supplies are estimated to have ranged from 6 to 12 percent at prevailing price levels.

[5] Marketing orders are a rather precise set of rules which prescribe how milk is to be marketed. They prescribe relationships among prices of various classes of milk, the geographic pattern of milk prices, and rules for how milk is to be marketed. For more detail, see Brooks, Karen, "Dairying and Dairy Policy in the 1980's," AEI Occasional Papers, American Enterprise Institute, Washington, D.C., 1984.

[6] See Hammond, Jerome W., Boyd Buxton, and Cameron Thraen, Potential Impact of Reconstituted Milk on Regional Prices, Utilization, and Production, Agricultural Experiment Station, University of Minnesota, Station Bulletin 529, 1979.

[7] Ibid.

U.S. grain policies also cause the dairy herd to be larger than it would otherwise be. These policies operate by means of deficiency payments. In effect, grain prices on the basis of which income transfers are paid to farmers are set above market-clearing levels. This causes the supply of grain to be larger than it otherwise would be. The larger supply comes on the market and in effect drives price down to the loan level, which is set lower than what would be market-clearing levels. This lower price is in effect a subsidy to the dairy industry, causing the cost of production for milk to be lower than it otherwise would be.

In recent years land has been pulled out of production as a means to reduce stocks in government hands and to raise the price of the grains. Whether prices have been increased to what would otherwise be their market-clearing levels is open to question, however. Policy should be to reduce this implicit subsidy and thus the incentives for a larger dairy herd than would otherwise be the case.

This same implicit subsidy affects the beef sector, and causes it, too, to be larger than it otherwise would be. The beef sector is in addition protected by a tariff, which in recent years has been converted in effect to a variable levy, and by the periodic negotiation of voluntary export agreements which limit imports. The sector is thus subsidized from two directions, both of which cause the beef herd to be larger than it otherwise would be. The protection of the beef sector is modest, but should be eliminated. Elimination of both kinds of subsidies would reduce the size of the herd and in turn the generation of greenhouse gases.

CHAPTER 3

SCIENCE AND TECHNOLOGY POLICY

Science and technology can also be used to reduce greenhouse emissions. For example, the biological fixation of nitrogen as a substitute for the use of commercial fertilizers would reduce the production of methane from these materials. Research to expand the biological fixation of nitrogen should thus be a part of policies designed to reduce the generation of greenhouse gases.

It may also be possible to develop fertilizer materials which release nitrogen more slowly. The available nitrogen would be absorbed more efficiently, thus reducing the amount released to the atmosphere.

More generally, research efforts directed to reducing methane emission from all of its agricultural sources should be expanded. This includes the emissions from fertilizers, from rice, and from the cattle herd.

An alternative approach is to develop new techniques for capturing and using the methane. At the height of the energy crisis in the 1970's, research on methane was augmented for this purpose. But resources for such research declined as energy prices declined in the 1980's. It is time these efforts were revitalized, but with the different goal of reduction of methane emissions.

Development of sustainable agricultural systems may be another way of reducing greenhouse emissions. Such systems require that nutrients be produced within the farm for on-farm commodities. The problem with this approach is that it tends to imply a slower growth in agricultural output than would be the case with plant nutrients purchased from the nonfarm sector. The costs of such a production system in terms of higher food prices could be quite high.

Current research on growth hormones for dairy cows offers another means to reducing cattle numbers. These hormones promise to increase production per cow by 25 percent or more with little additional feed intake. The potential for reducing cow numbers is thus great, even if the increase in productivity is reflected in lower milk prices, since the price elasticity of demand for milk is relatively low.

An important issue with this technological breakthrough is whether dairy farmers will permit the use of these hormones, or whether its use will be regulated or precluded entirely. Adjustment policies may be needed to help dairy producers shift to other income and employment opportunities. This points to the more general research and development issue of developing production alternatives that facilitate the shift of resources out of commodities that produce greenhouse gases.

Dealing with Externalities

Finally, methane emissions constitute a negative externality in that they impose social costs on others. Users of nitrogen fertilizers, producers of rice, and owners of cattle earn profits from those activities, but they don't pay all the costs incurred by society in their use and production since the greenhouse effect is "external" to their specific economic activities.

This is a classic problem in public policy. The solution to the problem is to impose a tax on the activity so the entrepreneur, whoever he or she may be, bears the full cost. Hence, the solution would be to impose a tax on the use of nitrogen fertilizer, and on the production of rice and cattle. This tax would reduce these activities to a socially optimal level.

The size of this tax should reflect the amount of external costs actually imposed by the activity. However, given the present state of knowledge, calculating the amount of the tax would be difficult.

To conclude, a number of policy actions are required to reduce greenhouse emissions from agriculture. The first is to reduce the subsidies that stimulate those activities which generate the emissions. The second is to increase R & D expenditures on those activities designed to reduce methane emissions and on activities designed to find ways to capture and make use of these emissions. The third is to tax those activities that give rise to methane emissions so as to reduce them to socially optimal levels.

Aside from political difficulties, the first two actions are presently feasible. The third is not feasible owing to the lack of an adequate knowledge base.

CHAPTER 4

POLICIES NEEDED TO HELP AGRICULTURE ADJUST TO THE GREENHOUSE EFFECT

If efficient use is to be made of this nation's agricultural resources, policies designed to facilitate the adjustment to greenhouse effects must take into account that these effects will be global in nature and that U.S. agriculture is part of a global economy.

The implication of the first point is that comparative advantage on a global scale will change significantly as a consequence of these effects. Regions of the world, including those in the United States, that were once efficient producers will no longer be so, while regions that previously were not efficient producers will become so.[8] Similarly, greenhouse effects eventually can be expected to have an impact on where populations and economic activities are located. This will change the location of the foci of demand, the other important dimension of comparative advantage.

The implication of the second point is that border-price pricing principles[9] should be followed so that the use of national resources is gradually adjusted to the changing conditions of comparative advantage. Subject to the caveats in the previous section and in sub-sections which are to follow, such principles will allow markets to bring about the needed adjustments. This is a proper policy to follow in light of the inadequate knowledge base on which policies will inevitably need to be developed.

Subject to the above constraints, a number of kinds of policies can be pursued to facilitate the needed adjustment. Each kind of policy and the principles which should guide it are discussed in the following sections.

Commodity Policies

The role of commodity programs in contributing to increased greenhouse emissions was discussed in the previous section. In that context the objective of policy was viewed as reducing the subsidies to activities which produce greenhouse emissions. In the present context the policy objective is similar, but the goal is different. The goal is now to have price and program policies which will permit agriculture to adjust to the changing conditions of demand and supply that evolve from the greenhouse effect.

The means to do that is to have policies which let domestic prices reflect border price opportunity costs. For export commodities such as wheat, corn, and soybeans, that will be domestic prices consistent with FOB export prices.[10] For commodities that compete with imports (beef, for example), it will be domestic prices consistent with CIF prices of imported commodities.[11] For non-tradeable commodities (the best example being a service, haircuts), conditions of domestic demand and supply, as conditioned by the demand and supply for tradeable commodities, should be allowed to work themselves out.

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[8] For an assessment of the greenhouse effects on Great Plains agriculture, see Ciborowski, Peter, and Dean Abrahamson, "The Granary and the Greenhouse Problem"; McQuigg, James D., "Climate Change and Agricultural Response: The Short Run"; and Rosenberg, Norman J., "Climate, Technology, Climate Changes, and Policy: The Long Run." All of these are in The Future of the North American Granary, edited by C. Ford Runge. Ames: Iowa State University, 1986.

[9] Border-price pricing principles assert that the domestic price of tradeable goods and services should be consistant with prices in international markets on the grounds that the latter prices reflect opportunity cost uses of resources. This is an efficiency criterion for the allocation of domestic resources.

[10] FOB prices are the prices of commodities at the port at which they leave the country.

The implication of such principles is that prices in the domestic economy should reflect conditions of demand and supply, and not be used as the means to transfer income to the agricultural sector. Similarly, commodity programs should not be used for price stabilization means. Neither of these propositions is to imply that equity or stabilization objectives should be ignored in the design of policy. What it means is that the price and market system should be permitted to do what it does best -- efficiently allocate scarce resources, while other measures are used to attain other policy goals. In light of the inevitable lack of adequate information to centrally allocate resources in the context of the expected changes in demand and supply induced by changes in climate, greater reliance on free markets is the only feasible alternative to pursue.

Present commodity programs also deter regional shifts in production of affected crops by means of acreage bases assigned to farmers as the basis of program management. The sector should be deregulated and these acreage bases phased out.

Income policies for agriculture should be made consistent with other welfare policies in the general economy. There is no inherent reason why income or welfare policies for agriculture should be any different than for the rest of the economy. The criterion of transparency requires that income transfers be direct and in the form of cash payments, and not in the form of implicit income transfers by means of distortions in prices.

Similar comments apply to price stabilization measures. There is little evidence to support a case for government intervention in the market for stocks as a stabilization measure.[12] As long as an adequate market information system is available and capital markets are reasonably efficient, the private sector can be expected to carry an adequate level of stocks, and to carry them in an efficient manner, so that markets will have the optimal level of stability. If it should be deemed necessary to carry a higher level of stocks than market forces will bring forth, modest storage subsidies paid on a per unit basis can increase the level of stocks carried with a minimal distortion to market forces.

Two factors argue for depending on market forces to reallocate resources in response to greenhouse effects. The first is that these effects are expected to be spread out over time. Resource reallocations are expected to be gradual, not abrupt and once-for-all. Markets are the most efficient means of pooling the enormous amount of data that will be generated as greenhouse effects emerge. The only caveat is that U.S. agriculture should be part of a global system of free markets so that border prices truly reflect global conditions of demand and resource scarcity. That is already a goal of U.S. policy. The potential seriousness of the greenhouse effect may provide added incentive to establish such policies globally.

Second, the consequences of errors in establishing prices by central means, or in imposing quantitative restrictions such as the amount of nitrogen per hectare, can be large, and errors can be expected to be frequent. Agriculture involves substantial fixed investments -- investments that have a long gestation period and that are relatively immobile. Mistakes in such investments can result in significant economic wastage.

Errors result from the centralized fixing of prices. No individual, or small group of individuals, can be expected to absorb and understand the large amount of information needed to fix prices, especially when climatic conditions are influencing those markets in unknown and uncertain ways. The only practical alternative is to depend on market forces.

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[11] CIF prices are the prices of commodities laid down at the port of entry.

[12] For a comprehensive treatment of the storage or stockpiling issue, see B. Gardner's, Optimal Stockpiling of Grain, Lexington, Mass.: Lexington Books, 1979.

Adjustment Policies

Greenhouse effects are expected to lead to significant geographic shifts in the location of economic activities, both within agriculture and within the nonfarm sector. Helping to facilitate the relocation of economic activities and the associated labor force is a legitimate role for government. Given that agriculture in the United States is largely a part-time activity, with some 72 percent of the income of farm families coming from nonfarm activities, adjustment policies for agriculture cannot be designed in isolation of activities in the nonfarm sector.

Consider first the issue of labor adjustment. Two kinds of policies are important. The first is retraining for new economic activities. This may be for new agricultural activities in a new location. It may be for non-agricultural activities in other regions. It may be for non-agricultural activities in the regions where labor is presently located. Or it may be to train the nonfarm labor force for agricultural activities in the regions where agriculture is expected to be more important as a consequence of climatic changes.

Members of the labor force can be expected to recoup some of the benefits of such retraining. Hence, it is approriate that individual workers pay some portion of these costs. However, a case can be made for government subsidies on the grounds of obtaining a more efficient allocation of resources and at a faster rate. Equity issues also enter since in the absence of subsidies a select group of individuals would have to bear the costs of adjustment that are a national issue, and not due to their own individual actions.

Government subsidies for retraining can take a variety of forms. One form is to provide the retraining at less than its full cost. Another form is to provide the trainees with fellowships and scholarships. Still another form the subsidy could take is to pay the trainee for attending the training program. This form of subsidy would address the fact that foregone income is frequently the most important private cost of participation in such programs.

Similarly, a case can be made for the government subsidization of relocation costs. In this case the subsidies might be in the form of moving costs, and for subsistence while individuals search for alternative employment. An important implicit subsidy for relocation is to maintain adequate information and technical assistance services for the labor market. These services should provide information to the labor force on where jobs are emerging and where they are declining. It should provide similar information to private and public businesses. And it should provide technical assistance to both employees and employers about how they can better take advantage of market opportunities.

Labor is not the only asset for which mobility will be an issue. Farmers in particular tend to have other assets, many of which are highly immobile. These include barns and other buildings, fences, drainage systems, and other site-bound assets. Assets such as tractors and equipment will be more mobile in a physical sense, but they may be obsolescent due to a change in economic activities associated with relocation. If a significant geographic area finds itself no longer vital in a particular economic activity, the widespread dumping of such assets can impose large losses on individual asset owners. These declines in asset values in regions losing comparative advantage can exacerbate the adjustment problem because they cause the declining area to be more competitive with newly expanding areas where the costs of production are expected to be higher on the margin.

Society faces a real quandary and challenge in dealing with these asset markets. To compensate all asset owners for the losses they incur due to changes in climate could be both difficult and costly. In the first place, it will be difficult to know what share of decline in asset values should be attributed to the greenhouse effects. The possibilities of moral hazard in which individuals insure only when the chances of loss tend to be highest, thus disturbing the actuarial base on which the insurance is issued, are great. So are the possibilities of errors in valuation, since there will be no markets to establish values. In addition, the costs of compensating for such losses can be very large.

An important issue will be whether alternative uses for the resources that might be used for compensation might have a higher payoff. For example, in a resource constrained situation, these same resources might have a higher social payoff in building the infrastructure in areas that are benefited by the change in climate, or in agricultural research designed to understand the impact of the change in climate and to develop varieties of crops better adapted to the changed climatic conditions.

On the assumption that greenhouse effects can be expected to be gradual and spread out over time, the best policy may be to not compensate for losses in asset values. The costs of the assets can be depreciated over their expected life, and the net income of the individuals will be compensated by means of income tax schedules. This system will require that sound information be made available on what the precise effects of the climate change will be, and their geographic locations.

If there should be acute, localized consequences of the greenhouse effect, compensation might be considered. This would be for such things as substantial increases in localized flooding or the sudden disappearance of water supplies.

The land market is another sector in which government intervention may be needed. Some areas may require the organization of land into larger farms so that the farm unit can provide an adequate income for the farm family. Other areas may require that farm size be smaller due to the emergence of agricultural activities that are more intensive. In the latter case, the market for land can probably accommodate the adjustments with relative ease. In the former case, a secondary market[13] may be needed to reorganize the resources efficiently. Whether this will be needed will depend on the expected speed of adjustment.

Finally, there is no a priori reason why the labor force should be forced to bear all the adjustment to changing economic conditions. For areas which experience a significant decline in agricultural activities, a surplus labor force can be expected to appear. Policy can promote the development of new economic activities in these regions as well as promote the relocation of labor. Retraining the labor force for such new activities will be an important form of subsidy for the relocation of non-farm activities. The provision of an adequate infrastructure such as roads, other transportation installations, and communication networks, is another. It is not clear that subsidies should go much beyond that, as long as an efficient local capital market is available.

Biocultural Restoration

Present analyses suggest that a significant greenhouse effect may lead to the virtual abandonment of agriculture in some parts of the United States. If such forces do indeed play themselves out, one can imagine a significant drainage of population from such areas and the virtual abandonment of some regions. Policies to reestablish some system of plant life on these abandoned lands will be important. In the first place, it may be the basis for a new set of economic activities. In the second place, it will be needed to prevent erosion and loss of topsoil. And finally, plants are consumers of carbon dioxide. Reestablishing as vital a plant life as is possible will be one means of minimizing the greenhouse effect itself.

To the extent that a new plant growth such as trees and shrubs should provide the basis of new economic activities, the private sector can be expected to handle it as long as they know what the economic opportunities are and capital markets are efficient. If that is not the case, then the government will need to take the lead in making investments and establishing vegetative growth which will control wind and water erosion and provide for plant cover. Such activities may be costly, but they are critical for conserving the basic resources for the future.

Irrigation Policies

An important aspect of the greenhouse effect is expected to be droughts and potential effects on water supplies. Measures to respond to these effects include our expansion in the area that can be irrigated and, if necessary, the capability to respond to a decline in available water supplies in a given area if the need for such a decline should occur. These actions will be fairly location specific, and will need to be implemented as more information becomes available on the regional and commodity specificity of the greenhouse effects.

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[13] A secondary market is one in which "third" persons acquire the land on the expectation of reselling it later at a gain, and with no intention of actually farming it. In effect they provide a floor under the market, while at the same time providing an efficient means of reorganizing the land into efficient sized farms.

More generally, measures which improve the efficiency with which irrigation water is used should be promoted. This should include pricing policies which price water at its true value. This is in stark contrast to present policies which price water at substantially less than its economic value and thus lead to substantial wastage. In addition, research and physical investments should be directed to reducing water losses, for example, trickle irrigation and instruments that help determine soil moisture.

Research Policies

The demand for new knowledge about how to adjust to changing conditions will be very great. Investments in the research to generate that knowledge may have as high a payoff as any investment the government can make.[14] Research should concentrate on generating new knowledge and information that is useful to both the private and public sectors.

The kinds of new knowledge needed are legion. The greenhouse effect itself needs to be better understood. Understanding its expected consequences should also be given high priority, especially on global comparative advantage. Such information is critical to enable the private sector to adjust efficiently to the changed economic conditions.

Research designed to produce new technology for a changed agriculture is also critical. Agricultural technology tends to be highly location-specific. In regions where agriculture becomes more vital as a consequence of the changes in climate, new technologies will need to be developed. In many cases this will require the development of a new capacity for agricultural research. In regions where agriculture declines, research will be needed to identify and develop the knowledge base for whatever vegetative and animal base will survive. In some cases, such new knowledge may be critical to establishing vegetative coverage of any kind.

Research should also focus on developing a more flexible agriculture. To the extent the changes in climate create more risk and uncertainty for farmers, they need farming systems with more flexibility, and which involve informal insurance schemes such as crop mixes in which the crops respond differently to climatic developments each year. A world of more risk and uncertainty may shift U.S. agriculture towards a combination of crops and livestocks on individual farms, and away from past trends towards specialization. Research on the inter-relationships among these enterprises will be needed.

Finally, there is a need for socio-economic research on a broad basis. This research should provide the knowledge base for devising sound socio-economic policies, and for facilitating the adjustment of the private sector to changed economic conditions. It should also focus on identifying changes in comparative advantage, both within the United States and on a global scale.

Other Issues

Three additional issues are important in helping society adjust to and adapt to prospective changes in climate from greenhouse effects. The first is the need for a sound information policy. The second is the need for a capacity for strategic planning to help establish policy as technical and economic conditions change. The third is the need for investments in infrastructure to accommodate a changed configuration of the economy. Some remarks on each of these issues follow.

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[14] The social rate of return to investments in agricultural research generally tends to be high, ranging from 35 percent to as high as 600 to 700 percent. See Ruttan, Vernon W., Agricultural Research Policy, Minneapolis, MN, University of Minnesota Press, 1982. With dramatically changed ecological conditions for agriculture and the need to do a great deal of adaptive research, the social rate of return to additional investments in agriculture could be expected to be quite high.

We proposed above that maximum reliance be placed on markets in bringing about the reallocation of resources associated with expected greenhouse effects. Markets can be expected to do this in an efficient way only if they have an adequate information base on which to respond. The provision of such information is a proper role of government. Hence, in addition to expanded research programs designed to produce new information and knowledge, it will be necessary to have an information system which makes this information fully available to members of society.

Such information is needed not only for men and women in their economic roles. It is also needed so that citizens can vote and act in an informed way on the issues. Hence, the information needs to be disseminated as widely as possible.

To accommodate the significant changes expected to come about as a consequence of climatic change, society needs a continuing capacity for strategic planning. This planning should be of a long-term nature, and designed to identify what the expected changes in the economy and society will be, and what resources will be required. This capacity need not be a large centralized organization. Some centralized means of coordinating the strategic analysis will be needed, however.

This nation is endowed with a remarkable set of land grant universities, most of which have Colleges of Agriculture. These Colleges, which tend to focus on problems of the state in which they are located, should be encouraged to take a longer term, strategic perspective to these problems, with particular emphasis on the potential consequences of climatic change. The U.S. Department of Agriculture has a unique analytical capacity in its Economic Research Service. This Service should also be encouraged to take a longer-term perspective focusing on climatic change. The Economic Research Service is also in a unique position to coordinate the research and analysis which goes on at the state level.

Finally, significant changes in the economy can be expected to bring about significant changes in infrastructure. Changed and new transportation and communication systems may be needed. New irrigation systems may be required, together with new drainage systems. And new systems in the form of formal adjustment policies and the institutions to implement them are required to accommodate the relocation of economic activities. It is a proper role of government to provide such facilities.

CHAPTER 5

CONCLUSIONS

Agricultural policies for climate changes induced by greenhouse gases need to focus on two broad classes of problems: (1) reducing greenhouse emissions from agricultural sources; and (2) facilitating the adjustment to the changes in climate in an efficient and equitable way.

Policies to deal with the first set of problems, in their order of importance, include: (1) deregulation of U.S. agriculture by the dismantling of present commodity programs and the shift to a more market-oriented agriculture, with closer integration of U.S. agriculture with the global agricultural sector; (2) shift of agricultural science and technology policy to give more attention to reducing greenhouse emissions; (3) promote the diversification out of rice production in the global economy; and (4) as appropriate, and as knowledge becomes available, use taxes and subsidies to internalize the external costs and benefits of activities which generate greenhouse emissions.

Policies to help agriculture adjust to changes in climate, in their order of importance, include: (1) commodity policies which facilitate the adjustment of U.S. agriculture to changing conditions of demand and supply in the global economy and in the United States; (2) explicit adjustment policies which facilitate the adjustment of labor to changed employment opportunities and which support other agricultural input markets; (3) expanded and redirected agricultural research programs to generate new production technologies for agriculture, to better understand the aggregate adjustment problem agriculture will face, and to facilitate adjustment at the individual farm level; (4) an expansion in irrigable area and measures that make for a more efficient use of available water supplies, including increased investments in irrigation and water use and management; (5) more strategic planning to make for a more efficient and equitable longer-term adjustment of agriculture; (6) a strengthened information system on the consequences of climatic change so individual citizens can vote more intelligently on the issues and can adjust their own economic activities in their own best interests; (7) construction of new infrastructure in regions that become newly adapted to agricultural activities; and (8) biocultural restoration in areas in which agriculture declines as to conserve resources for the future.

Timing is an important issue in taking action to reduce agricultural sources of greenhouse emissions and in helping agriculture to adjust to possible greenhouse effects. There are lags in the build up of possible effects, and similar lags in the response to any measures taken. Moreover, some of the measures proposed, such as increased investments in agricultural research, have long gestation periods. In the case of agricultural research in particular, the lag between increased expenditures on research and effects on farmers' fields is from six to ten years.

Measures to reduce agricultural sources of emissions and to help agriculture adjust to possible greenhouse emissions should thus begin immediately. An important feature of the measures that have been outlined above is that most of them are in the best interest of the nation in their own right, and that they improve the efficiency with which the nation's agricultural resources are used. The efficiency gains provide the basis for a more rapid rate of economic growth, and thus provide the resources for dealing with greenhouse effects if and when they come.

Finally, the extent to which a possible greenhouse effect is a global problem means that steps toward international cooperation in dealing with the problem should begin immediately. A sense of urgency and immediacy is especially important in addressing the problems associated with the agricultural sector.